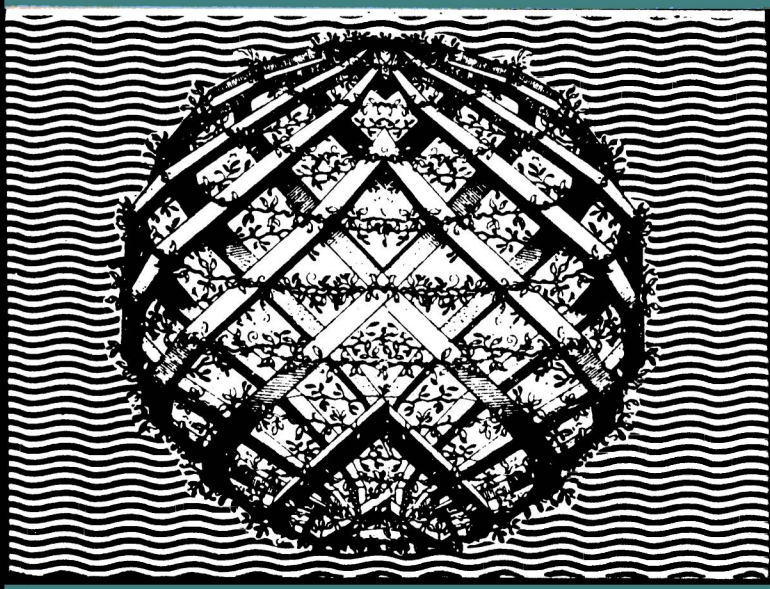
The World's Water

Mir Publishers
Moscow



M.I. Lvovich

MIR PUBLISHERS of Moscow publish Soviet scientific and technical literature in four languages—English, French, Spanish and Arabic. Titles include textbooks for universities, technical schools and vocational training, literature on the natural sciences and medicine, including textbooks for medical schools and schools for nurses, popular science, and science fiction. The contributors to Mir Publishers' list are leading Soviet scientists and engineers in all fields of science and technology and include more than 40 Members and Corresponding Members of the USSR Academy of Sciences. Skilled translators provide a high standard of translation from the original Russian. Many of the titles already issued by Mir Publishers have been accepted as textbooks and manuals at educational establishments in India and other countries.

Mir Publishers' books in foreign languages are exported by V/O Mezhdunarodnaya Kniga and can be purchased or ordered through booksellers in your country dealing with V/O Mezhdunarodnaya Kniga, USSR.

ИЗДАТЕЛЬСТВО
МИР

М. И. Львович

ВОДНЫЕ РЕСУРСЫ БУДУЩЕГО

Издательство
«Просвещение»
Москва

новое в науке

The World's Water

Today and Tomorrow

Mark Lvovich
Professor, Doctor of Geographical Sciences

Translated from the Russian
by Leonard Stoklitsky

Mir Publishers
Moscow

UDC (551.49) = 20

© English translation,
Mir Publishers, 1973

First published 1973
Revised from the 1969
Russian edition

На английском языке

Л $\frac{0296-235}{041(01)-73}$

Contents

INTRODUCTION 7

Chapter One
HOW MUCH WATER IS THERE? 12

Chapter Two
THE HYDROLOGIC CYCLE 20
General Features 20
Atmosphere 22
Oceans 25
Lithogenous Arc 27
Soil 34
Rivers 42
Lakes and Reservoirs 59
Biological Arc 61
Water Exchange 70

Chapter Three
THE WATER BALANCE AND WATER RESOURCES 72
The World's Water Balance 72
Water Balance of the Land Area 75
Fresh Water Resources 78
Zonal Patterns 90
Local Features 94
Today's Water Resources 98

Chapter Four
MAN'S IMPACT ON THE HYDROLOGIC CYCLE . . 108
How Water Resources Are Used 108
Long-Range Forecasting 113
Public Water Supply 116
Irrigation 133
Water in Non-Irrigation Farming 139
Hydropower and Navigation 144
Fishing 149
Recreational Uses 152
The Key to Clean Water 154
The Essence of the Multipurpose Approach 158
Hydroeconomic Problems 160

Chapter Five
CONTROLLING THE HYDROLOGIC CYCLE 165
Possible Trends 165
Reshaping the Local Water Balance 168
Forests and the Water Balance 176
Changing the Regimen of Rivers 179
Man Stores Groundwater 185
Transportation of Water 187
Water Resources and Moistening Rhythms 191
Tomorrow's Water Balance 192

Chapter Six
WILL THERE BE ENOUGH WATER TOMORROW? . . 199

BIBLIOGRAPHY 210

Introduction

In this age of economic growth coupled with population growth more and more regions of the world are finding their water resources insufficient. The time is approaching, some experts predict, when man will not be able to get sufficient supplies from rivers and groundwater, the sources he has drawn on through the ages, and therefore he must seek other sources.

One cannot say there is no foundation for that view. Man has made quite a few blunders in water use and conservation, the worst of them being massive pollution of lakes and rivers. Pollution is the main factor that threatens exhaustion of water resources. Each cubic metre of sewage dumped into a river or lake contaminates dozens of cubic metres of clean water. Abundant water resources are of little use if they are polluted, for pollution makes them a health hazard.

Concern about the future of water resources has been expressed in an increasing number of articles and books in recent years.

Before we can plan water use and conservation with a view to meeting all domestic, industrial and other

needs, we must analyse just how present-day methods of water management will affect tomorrow's water resources.

An analysis of this kind makes it clear that if today's policies are continued they will inexorably produce a situation in which it will be extremely difficult to meet the diverse and growing demands for water.

Yet there are people who claim that the present-day principles of water use and conservation do not require any significant modification. For example, the authors of a water use plan for the United States in the year 2000 proceed from that assumption,[1] with pessimistic conclusions concerning the adequacy of the water resources.

The expansion of the chemical, oil, ore mining and other water-consuming industries, urban growth and the increasing use of water in farming greatly complicate the problem. To prevent the resources from running out we must fundamentally change our approach. The time when demand was low and comparatively easy to meet has passed.

Before we can draw up effective guidelines we must calculate the world's water resources with the greatest possible accuracy. Assessment of the resources is often based on the amount of water in the different parts of the hydrosphere. Actually, this yields a far from complete picture inasmuch as the resources *are in a process of constant renewal within the hydrologic cycle.* Therefore, besides examining the reserves in the various parts of the hydrosphere at any one time, we shall examine in detail the water balances of the world as a whole and of the Soviet Union in particular, to give the reader a better idea of the resources.

Hydrological investigations along geographical lines carried out during the past decade or so help to solve a number of problems connected with rational multi-

purpose water use and conservation. Hydrologists have developed a method of studying the water balance that takes into account the subterranean arc of the hydrologic cycle. They have investigated zonal and local water balance patterns, compiled charts of the water balance elements of the Soviet Union and the continents of the world, and drawn up a balance-sheet of the water resources of the Soviet Union and the world as a whole. They are now studying ways and means of influencing the hydrologic cycle, for one thing, by acting on its soil component through farming practices and forest improvement. Principles underlying the planning of a water management budget have been drawn up.[2]

The results of these studies are set forth briefly in the present book.

Our chief conclusion is that *the water resources on earth fully suffice to meet all of man's steadily growing needs for an indefinite time.* But man must strictly adhere to a correct policy of using water and reshaping the hydrologic cycle and water balance. He must practise *extended reproduction* of suitable water resources.

All previous experience shows that man must cease to regard water resources as an inexhaustible gift of nature. The resources are indeed inexhaustible—but only if used with the greatest care and if proper attention is paid to their conservation. They are extremely vulnerable to negligence. They are quickly depleted if careless or incorrect conservation is practised.

It is most important to correlate demand with the available resources. In many parts of the world the demand exceeds the physical possibilities of meeting it. Extended reproduction of water resources can improve the situation, but only up to a point. The availability of water resources is an important indicator

of the economic level of a country, but water also has great significance apart from the economic sphere, as a component of the environment. Unless we take this into account we cannot understand the proper methods of water utilization and the exceptional importance of its conservation.

Various ways of solving the water problem have been proposed. Some suggest desalination of sea water as the way out, some maintain that sewage treatment is the one and only solution, and some pin their hopes on diverting water from well-supplied areas to regions whose water resources were either poor to begin with or have been exhausted. All these are good ideas, but only as part of a broad complex of diverse and purposeful steps that should be carried out by all sectors of the economy on the recommendation and under the guidance of a single national centre.

The author does not believe that the water problem can be solved by one-sided measures. He strives to show, in this book, that a water crisis can be averted by an integrated programme of technological, biological and organizational measures.

We shall present concrete examples to illustrate the water management principles that will ensure enough resources to meet future requirements notwithstanding a substantial population increase and economic growth. We do not, of course, claim that our assumptions concerning the year 2000 are precise. The important thing is to assess the possibility of providing water for a population, agriculture and industry at a level of development much higher than the present one. When we speak of the year 2000 we do so in a relative sense. In any event, there will sooner or later come a time when water management will have to meet a demand far greater than that of today.

The book discusses principles of water use and con-

servation that follow from an analysis of conditions to be expected in the future. We do not regard these principles as final or complete. Considerable research will be required to work out, comprehensively and in sufficient detail, the basic propositions of a technical policy of water use and conservation.

In recent years the Communist Party and the Soviet Government have passed a number of important decisions concerning development of the Soviet water economy.

Of particular significance are the decisions of the 24th Congress of the Communist Party of the Soviet Union in the spring of 1971, which pointed to the need for correct solution of the problems of water use and conservation of the environment. Soviet science is equipped with an advanced theory of the planning and use of natural resources, a theory that dates back to Lenin's programme for the electrification of Russia. In order to translate the theory into practice in the most rational and economical way, we must first chart the main trends in the use of water resources and in management of the hydrologic cycle. It is up to science to point the way to solving this cardinal problem.

CHAPTER ONE

How Much Water Is There?

The sum-total of all water on earth makes up what is known as the *hydrosphere*. This can be defined as the aqueous envelope of the earth, including the oceans, lakes, streams and underground waters, polar and mountain glaciers, soil moisture and the water vapour in the atmosphere.

There are three other spheres on earth: the atmosphere, the biosphere and the lithosphere. All four interpenetrate and are in close and constant interaction.

The seas, or world ocean, as they are sometimes called, cover 361,000,000 square kilometres, or 70.8 per cent of the earth's surface. Land accounts for 29.2 per cent of the earth's surface, less than one-third of the total.

With an average depth of 3,800 metres, the world ocean has a total volume of a little more than 1,370 million cubic kilometres.

Average salinity of sea water is 3.5 per cent. It ranges from zero near the mouths of large rivers to 4 per cent in tropical seas having a low rate of water exchange with oceans. The salts in sea water are most-

ly chlorides (88.7 per cent). Next come sulphates (10.8 per cent) and carbonates (0.3 per cent). There are negligible amounts of aluminium, iron and a number of other substances.

The volume of surface water of the land area (lakes and rivers) is very small compared with that of the seas. Inland water occupies less than 3% of the world's land area. Total volume of lake water amounts to 230,000 cubic kilometres and total river water to only 1,200 cubic kilometres. Yet, as we shall see later, streams are probably the most important of all water resources from the economic point of view.

Glaciers cover more than 16,000,000 square kilometres, almost 11 per cent of the land area, and, according to recent data, contain about 24,000,000 cubic kilometres of water. All other ice contains about 250,000 cubic kilometres of water, including approximately 200,000 cubic kilometres in soil ice, chiefly in the permafrost zone. The 35,000 cubic kilometres or so of sea ice and icebergs are included in the volume of ocean water, and the 1,600 cubic kilometres of atmospheric ice are part of the volume of water vapour.

Until recently the aggregate volume of all the world's glaciers was estimated at between 28,000,000 and 29,000,000 cubic kilometres. The latest findings put the figures at 4,000 to 5,000 cubic kilometres less. This appreciable revision was made after the discovery of the mountain ranges buried under the Antarctic icecap.

If all the ice on earth were to melt, the level of the seas would rise by 64 metres and their area would increase by almost 1,500,000 square kilometres, reducing the land area by one per cent.

The volume of all surface waters of the land area, including glaciers, amounts to about 25,000,000 cubic

kilometres. This is 55 times less than the volume of the world ocean.

The amount of underground water is harder to determine. According to Vinogradov[3] the earth's mantle contains 0.5 per cent water, which would make the total volume between 13,000 million and 15,000 million cubic kilometres at the least, or about 10 to 12 times more than the water in the seas. This water, bound chemically and physically to minerals and rocks, feeds the water of the earth's crust and the surface water.

Water discharge into the crust and to the surface from deep-lying strata of the earth's mantle is estimated at an average of one cubic kilometre a year by Makarenko[4]. Since the age of the earth's crust is about 3,500 million years, the entire volume of surface water and water in the crust should be about 3,500 million cubic kilometres.

Vernadsky estimated all the water of the earth's crust at 1,300 million cubic kilometres, which is about the same amount as in the seas. But a considerable quantity of the water in the crust is chemically bound to minerals, that is, comprises part of them. Vernadsky assessed the volume of free water in the upper crust at 60,000,000 cubic kilometres.

Makarenko's recent estimates show that there are 84,400,000 cubic kilometres of water in the five-kilometre layer of the earth's crust underneath the land area; this amounts to 12 per cent of the volume of that layer. Not counting the bound water, Makarenko sets the total volume of gravitational water in that layer at 60,000,000 cubic kilometres, which agrees with the figure given earlier by Vernadsky.

The American hydrologist Raymond Nace estimates the amount of underground water at 2,000,000 cubic miles (4,170,000 cubic kilometres), half of it being

within a depth of half a mile (800 metres) and the other half below that level[5]. Nace's total is undoubtedly an underestimate, but his figure for the proportion of subsurface water within a depth of half a mile is evidently close to the truth. We accept it, but round off the figure to 4,000,000 cubic kilometres, which we classify in the zone of active water exchange.

It is clear from the above that our idea of the amount of underground water is still very approximate. The discovery of a theoretical key to estimating its volume was a major scientific achievement. This is much more complicated than determining the volume of the world ocean, where accuracy depends on the number of depth soundings taken. So many echometer soundings of the seas have been made in the past few decades that we can hardly expect any appreciable adjustment in estimates of their volume in future.

Methods of calculating the volume of subterranean water, however, will undoubtedly be improved. Deep drilling holds forth particular promise. Boreholes three and four kilometres deep are no longer unusual. We have learned to drill to a depth of seven kilometres, and when a large number of such wells have been sunk we shall gain a more definite idea of the volume and nature of the subsurface waters.

The chemical composition of underground water ranges from pure fresh water to deep-lying, highly concentrated brine containing more than 250 grams of salt per litre of water. Sodium chloride water predominates; sodium calcite waters and waters containing sodium and magnesium occur less frequently. Fresh water is rarely found at great depths; at more than one and a half or two kilometres the water is saline as a rule. In semi-desert and desert regions, however, saline water frequently occurs closer to the

surface, with lenses of fresh water from rain or snow often floating on top of them. The fresh water seeps down from the surface and, because its density is lower, does not mix with the saline water. After studying lenses of fresh underground water in the Kara Kum Desert of Central Asia for many years, V. N. Kunin[6] worked out scientific principles of utilizing it.

In the zone of *permafrost* underground water exists in a solid state as ice at depths of up to 500 metres and sometimes more. This phenomenon is widespread in the northern and northeastern areas of the Asian part of the Soviet Union and near the Arctic Circle in North America.

Subsurface waters are divided into several groups according to the degree to which they take part in the hydrologic cycle. They range from stagnant waters, whose age is the same as the age of the rock that contains them, to seasonal waters, which form in moist periods and disappear in dry periods.

The total amount of groundwater in the zone of active exchange is, as we have said, approximately 4,000,000 cubic kilometres. The capacity of this zone is chiefly connected with the depth of the downcutting of the river valleys and river channels that drain the groundwater. Instances of the active exchange zone dropping lower than the downcutting of river valleys are far from rare, however. This happens in places where artesian groundwater occurs.

Soil moisture is more closely dependent on weather conditions than groundwater. Much water is retained in the soil in rainy seasons, but it quickly evaporates in dry seasons. In addition, the distribution and regimen of soil moisture are more closely linked up with biological processes. One of the chief features of the composition of the soil is that it contains organic substances which strongly influence its hydraulic

properties. Water is part of the composition of the soil, and, along with humus, is one of the elements of soil fertility. The biological productivity of an area depends to a substantial extent on soil moisture. If there is insufficient moisture, plants lack water and crop yields decline. Too much moisture waterlogs the soil and hampers the growth of cultivated plants and forests.

The total volume of soil moisture is estimated at about 83,000 cubic kilometres. Although this is not much when compared with other parts of the hydrosphere, soil moisture is of major importance to cultivated and wild plants, and therefore to human life. About half of the world's land mass suffers from a shortage of soil moisture to some degree. Man takes steps to increase and regulate soil moisture in order to increase crop production. These include scientific farming methods and also irrigation, which is being applied on a growing scale. There are now some 220,000,000 hectares of irrigated land in the world.

Most of the atmospheric vapour lies inside the troposphere, which reaches to an altitude of 16 to 18 kilometres in the equatorial zone, 10 to 12 kilometres in the temperate latitudes and 7 to 10 kilometres in the polar latitudes. Above that, in the stratosphere, there is practically no water vapour at all. The total volume of atmospheric vapour is about 14,000 cubic kilometres. However, as a result of the continuous interchanges in the hydrologic cycle, in the course of a year this water produces precipitation almost 40 times greater in volume.

The world's rivers contain only 1,200 cubic kilometres of water. True, drainage lakes, having a total volume of 125,000 cubic kilometres, are connected with rivers. Drainless saline and brackish lakes have a volume of about 105,000 cubic kilometres.

TABLE 1

COMPOSITION OF THE HYDROSPHERE

	Volume (in thousand cubic kilometres)	Per cent of total volume
World ocean	1,370,323	93.93
Underground water, total	60,000	4.12
of which groundwater in zones of active exchange	4,000	0.27
Glaciers	24,000	1.65
Lakes	230	0.016
Soil moisture	83	0.005
Atmospheric vapour	14	0.001
Rivers	1.2	0.0001
Total	1,454,651	100

As can be seen from Table 1, the combined instantaneous volume of water in the hydrosphere amounts to nearly 1,500 million cubic kilometres. The world ocean accounts for almost 94 per cent of the total, and the water of the world's land area for 88,320,000 cubic kilometres, or some six per cent. Fresh water, including roughly 8,000,000 cubic kilometres of underground water, amounts to about 32,200,000 cubic kilometres, only a little more than two per cent of the hydrosphere.

A point worth bearing in mind is that the figure given in the previous paragraph for fresh water includes an enormous volume of water in the form of ice in the polar glaciers. At present, man is unable to use this water. The amount of fresh water that man actually uses comprises only 0.3 per cent of the hydrosphere. This minute share of the hydrosphere plays the main part in human life and the economy.

We do not wish to imply, of course, that other parts

of the hydrosphere are not used. The seas are important in transport and as a source of fish. Sea water is used, although on a small scale, for technical purposes as well, for example, to condense steam at thermal power plants. Inland seas, such as the Caspian and the Sea of Aral, are of considerable economic importance.

Pointing to the insignificant proportion of fresh water in the hydrosphere, pessimists conclude that a water famine threatens mankind. The fact that there is only a small amount of fresh water does not, however, constitute any threat at all. It is not so much the actual amount of fresh water in the hydrosphere that counts, as the amount of what we call the "dynamic reserve", that is, the water taking part in the hydrologic cycle.

Whatever danger there may be of a water famine arises rather from inefficient use of the resources than from a lack of water in the world. And that is just the problem with which this book deals. We shall be returning time and again to ways and means of preventing the depletion of water resources.

CHAPTER TWO

The Hydrologic Cycle

GENERAL FEATURES

The hydrologic cycle links up all parts of the hydrosphere—the seas, lakes and streams, groundwater, soil moisture, atmospheric vapour—into a single whole.

Water evaporating from the surface of the seas and land enters the atmosphere in the form of vapour, which later condenses and produces rain or snow. Part of the rain and melted snow seeps into the soil. The rest becomes what is called surface runoff, which flows down slopes and gathers in ravines and gullies into numerous rivulets that discharge into rivers. Rivers are continuously fed by groundwater, whose reserves are renewed when soil moisture percolates downwards to the zone where the pores of rocks and sediments are completely saturated with water. Part of the groundwater rises to the surface in the form of springs or is drained by rivers.

Lakes and seas are replenished not only by precipitation but also by river water. In this way, evaporation losses are continuously offset. The soil moisture that is evaporated or is transpired by plants enters the atmosphere in the form of vapour.

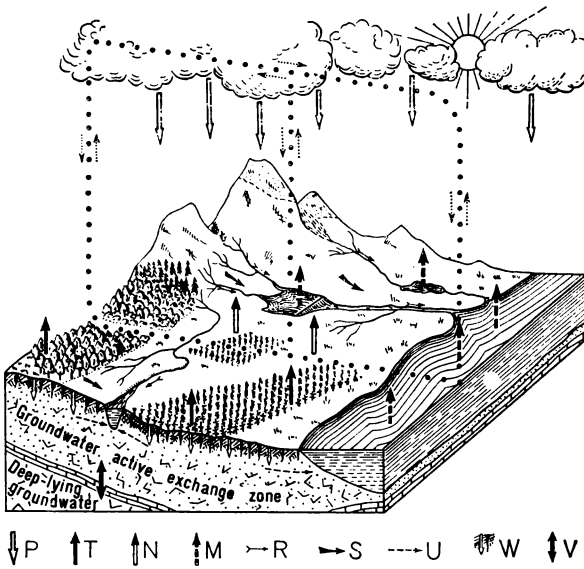


Fig. 1. Hydrologic cycle: *P*—precipitation; *T*—transpiration; *N*—soil evaporation; *M*—evaporation from water surface; *R*—total river flow; *S*—surface (flood) runoff; *U*—groundwater (permanent) discharge into rivers; *W*—overall soil moistening; *V*—exchange with groundwater lying below river drainage level

The hydrologic cycle is a continuous global process. Many natural phenomena are involved in it, among them soil formation, plant growth and the shaping of the terrain by erosion. Water use for various economic and domestic purposes also enters into the hydrologic cycle.

Thermal energy and gravitation are the cyclemotive forces. Heat causes evaporation, the condensation of water vapour and other processes. Terrestrial

gravitation is the force that makes raindrops fall and rivers flow. These two forces often operate together. For example, atmospheric circulation is influenced both by thermal processes and gravitation.

The hydrologic cycle consists of a chain of arcs and chords, the main ones being the atmosphere, the oceans, the continents, including a lithogenous arc, the soil, rivers, lakes, glaciers and the biological and economic arcs.

ATMOSPHERE

In the atmospheric arc of the hydrologic cycle, moisture is transported in the process of atmospheric circulation, and precipitation is formed. Atmospheric circulation is comparatively stable from year to year, although seasonal variations may be considerable. In the equatorial belt, in the zone of a powerful ascending air current, there is heavy precipitation, chiefly in the form of torrential rains. Here, rainfall is distributed fairly evenly throughout the year. Between 1,500 and 3,000 millimetres of rain falls annually on most of the territory. The world's largest rivers, the Amazon and the Congo, are situated in this zone. More precipitation is registered in their basins than in the basins of the other big rivers in the northern and southern hemispheres.

Dry weather predominates in the trade wind belts in the tropics. Here there is little precipitation, and deserts cover large areas. In the northern hemisphere, for example, there are the Sahara Desert and the desert in California, and in the southern hemisphere the Kalahari, Atacama and Australian deserts. Less than 100 millimetres of precipitation a year falls in some areas of these deserts, while in some places (Lima in Peru, Aswan in Egypt, and others) there may be no precipitation for several years in a row.

Some regions in the tropics, where winds blow landwards from the ocean, have huge amounts of precipitation. More than 11,000 millimetres a year falls on Cherrapunji, India, and more than 12,000 millimetres on the Hawaiian island of Kauai. This is quite an impressive layer of water, equal to the height of a three- or four-storey building. In the zone of the trade winds, a great deal of precipitation falls on the eastern parts of the continents.

In the subtropics there is a clear-cut difference between the amount of precipitation in inland regions and in the oceans and coastal areas of the continents.

Precipitation is more evenly distributed in the temperate zones. In regions having a marked oceanic influence the precipitation is heavier and shows less seasonal fluctuation. Less precipitation is registered in the interior, where most of it falls in the warmer part of the year. There is little precipitation in the polar regions and adjacent areas. Less than 50 millimetres of snow falls in the central part of the Antarctic in a year. Average annual precipitation in the polar regions ranges between 100 and 300 millimetres, most of it snow.

From the hydrological point of view it is important that part of the precipitation in the temperate zones is snow, which accumulates on the ground in winter. Rivers are not, as a rule, fed by surface runoff in this period but by groundwater. When the snow cover melts in spring it produces from 100 to 300 millimetres of water in a comparatively short time, creating spring floods on the rivers.

It was discovered not so long ago that precipitation gauges give distorted readings in windy weather, particularly during snowfall. The Soviet Union's Central Geophysical Observatory has developed a method of correcting the readings to account for the

wind. Another source of inaccuracy is wetness of the gauges. Every time a gauge is emptied, some water, equal to 0.2 millimetres of precipitation, remains on its walls. If the gauge is emptied 100 times in the course of a year, its readings are 20 millimetres less than the actual amount. This is four per cent if the annual total is 500 millimetres.

Overall corrections usually fluctuate between 5 and 20 per cent depending on the amount of solid precipitation, wind velocity, degree of wind protection of the gauge and frequency of rainfall. In areas with much heavy rain the corrections are relatively smaller. All this, however, will not appreciably alter our idea of the amount of precipitation falling on large land areas. In regions where precipitation has not been sufficiently studied, data on streamflow, corrected for evaporation losses, are used to verify the amount of precipitation. This applies especially to mountainous areas, where the river basins can be likened to gigantic rain gauges.

Calculations show that the average precipitation is 760 millimetres on land and 1,140 millimetres on the seas. This makes an average of 1,030 millimetres, or just over one metre. In volume the corresponding figures are 113,500 cubic kilometres (22 per cent) on land, 411,600 cubic kilometres (78 per cent) on the seas, and 525,100 cubic kilometres on the globe as a whole.

Atmospheric precipitation, summed up in the above figures, gives rise to many other processes in the hydrologic cycle.

Air circulation plays a direct role in the cycle by distributing atmospheric moisture across the earth. Precipitation on the continents exceeds the amount of moisture the atmosphere receives from them through evaporation. The difference, amounting to about 40,000

cubic kilometres annually, is made up by the transfer of atmospheric moisture from the seas to land. This is an important process since it increases the water resources of the continents. Without this additional moisture man would be much poorer in water resources.

OCEANS

Evaporation, the most characteristic feature of the oceanic arc of the hydrologic cycle, continuously replenishes the water vapour in the atmosphere. More than 86 per cent of the moisture that enters the atmosphere evaporates from the surface of the world ocean and less than 14 per cent from the land areas.

That oceanic evaporation is not evenly distributed can be seen from the difference between evaporation and precipitation. In the equatorial zone, evaporation discharge is less than annual precipitation, owing to great cloudiness. In the temperate zone, evaporation is also less than precipitation but here the main reason is insufficient warmth. In the tropical and subtropical zones, more moisture evaporates from the surface of the seas than falls in precipitation. That is because in the trade wind belts cloudiness is less frequent, the climate is very warm, and there is relatively less precipitation.

The movement of enormous masses of sea water is an important feature of the oceanic arc of the hydrologic cycle. The amount of water carried annually by the currents of the four oceans is shown in Table 2.

The last column gives the average number of years required for all the water in an ocean, and in the world ocean as a whole, to mix or to be replaced. For the world ocean it is about 60 years. Water exchange is least intensive in the Pacific Ocean, where the total number of years required exceeds 100. For the Atlantic the figure is

TABLE 2

WATER CARRIED BY OCEAN CURRENTS AND INTENSITY OF WATER EXCHANGE

	Area in million sq km	Volume in million cu km	Annual flow in million cu km	Water exchange intensity — ratio of annual flow to ocean volume (number of years)
Pacific	180	725	6.56	110
Atlantic	93	338	7.30	46
Indian	75	290	7.40	39
Arctic	13	17	0.44	38
World ocean	363	1,370	21.70	63

about 50 years, and for the Indian and Arctic oceans about 40 years each.

Little was previously known about the rate of oceanic water exchange since the velocity of the currents and the amount of water they carried had not been sufficiently studied.

In recent years the Soviet Union's *Vityaz* and *Mikhail Lomonosov*, the American *Argo* and other research vessels have discovered and measured strong trade-wind currents and equatorial counter-currents that move eastwards. These currents run at a depth of several hundred metres and are as much as 300 kilometres wide.

The flow of the counter-currents is estimated at 110 to 120 million cubic metres per second, and annual flow at something like 3,500,000 cubic kilometres. The counter-currents have not been thoroughly studied, however, and the actual figures are probably higher.

Oceanic currents influence the hydrologic cycle

chiefly through the climate. They carry 20,000 times more water than the world's rivers, and the water exchange they bring about is 1,500 times more intensive than that caused by atmospheric precipitation falling on the ocean. The internal oceanic water exchange is much more intensive than the external exchange connected with the fresh-water cycle.

We shall return to these figures when we examine the rates of water exchange in the hydrosphere.

LITHOGENOUS ARC

The lithogenous arc of the hydrologic cycle, in other words, the participation of groundwater in the cycle, has many different aspects. Deep-lying groundwater, chiefly brine, is hardly connected at all with the upper layers of groundwater or with other arcs of the hydrologic cycle. It is often as old as the rock containing it. In some areas deep-lying groundwater accumulated for millions of years. It percolated downwards, drop by drop, and combined with water squeezed up out of the earth's mantle to form vast reservoirs, usually at depths of one or two kilometres and more. Deep-lying groundwater takes practically no part in the hydrologic cycle and is to all intents and purposes stable. Its volume changes insignificantly over short periods of time. Its mineral content is usually very high.

Fresh groundwater lies chiefly in the zone of active water exchange, in the upper part of the earth's crust, which is drained by river valleys, lakes and seas.

Natural drainage of groundwater plays a great role in the hydrologic cycle. It regulates the rivers by feeding them steadily. Without this source, river regimens would be even more changeable. Rivers would dry up except when it rained or snow melted, like

those in arid steppeland and deserts. Owing to poor groundwater recharge in the lower Volga basin and the plains of Kazakhstan, such comparatively large rivers as the Maly Uzen, the Bolshoi Uzen and the Nura flow only for a short time in spring and are dry in the other seasons of the year. Similarly, river beds in the Sahara and Kalahari deserts may be dry for several years and then turn into torrents during cloudbursts. The resources of these rivers can be used only by building large reservoirs to collect the flood waters and act as regulators in place of the non-existent groundwater.

The amount of annual groundwater recharge in the process of the hydrologic cycle can be established on the basis of water balance estimates. It cannot, as yet, be determined through hydrogeological study. Boreholes drilled down to the layers of groundwater, calculations of the thickness of the layers, the discharge of the boreholes and the velocity of groundwater flow, and other hydrological investigations do not reveal the amount of groundwater taking part in the hydrologic cycle.

How much water is renewed in some artesian reservoirs can be assessed through years of use and observation. By calculating the amount of groundwater drawn up and observing the water table it is possible to estimate the recharge. If the water table remains stable over many years it shows that the amount of water removed does not exceed the renewed storage. If the water table drops steadily from year to year this shows that pumpage exceeds recharge.

This indicator, however, is not always reliable for extensive artesian reservoirs in which separate sections are tapped. A drop in pressure or a drop in the water table on comparatively restricted sections is sometimes due to the formation of depression funnels. Such funnels appear when the water pumped out of a drilled

well is not replaced fast enough by water from the adjacent parts of the aquifer, or water-bearing formation. When the well is not used, the funnel gradually fills up. The velocity of groundwater movement and the well's discharge are judged from how fast the funnel fills up. This method, however, does not tell us how much groundwater takes part in the hydrologic cycle and is renewed annually.

A general idea of those amounts has been obtained by studying the natural drainage of groundwater by rivers. Groundwater accounts for the most stable part of streamflow. To estimate how much of streamflow is groundwater, hydrologists use a method based on an analysis of regular streamflow observations.

Although not yet precise, these data give an approximate picture of the groundwater stores that are renewed regularly in the hydrologic cycle. The data are valid if groundwater discharge by other routes is insignificant.

Groundwater discharge takes place in several ways. First, some groundwater moves below the level of river drainage and is discharged directly into the sea. This chord of the groundwater arc of the hydrologic cycle has been little studied but there is reason to assume that the amount of direct groundwater outflow into the sea, bypassing rivers, is not large compared with the amount drained by rivers.

We can judge this, for example, by the groundwater regimen on seacoasts. On the Netherlands coast of the North Sea, fresh groundwater occurs where dunes are widespread, but it is backed by saline groundwater that penetrates into the continent from the sea. Increased withdrawal of fresh groundwater causes a flow of sea water into wells.

When a comparatively small amount of continental groundwater is used for water supply none reaches the

sea and it is replaced by sea water that seeps into land. This happened in Long Island (New York) when the groundwater resources were depleted through use in the water supply system. Fresh groundwater was gradually replaced by sea water. Storm flow is now being pumped underground to force out the sea water.

The Caspian Sea is another example. Of the 300 cubic kilometres or so of water that flows into the Caspian, only about five cubic kilometres, or less than two per cent, is groundwater that does not pass through rivers. The volume of water reaching the Caspian after being drained by rivers amounts to about 120 cubic kilometres annually, which is 40 per cent of the total inflow into the sea.

Approximately the same situation obtains on the Netherlands coast of the North Sea, where comparatively little groundwater reaches the sea directly but where the Rhine and other rivers flowing into the sea carry a large amount of groundwater drained by them throughout their length and by their farflung network of tributaries.

More groundwater reaches the seas from coastal mountain ranges, such as the Rocky Mountains and the Andes stretching along the Pacific coast of North and South America. On the Caucasian coast of the Black Sea fairly strong groundwater springs emerge on the shore and below sea level. Similar emergence of groundwater occurs in the coastal area of Yugoslavia and part of the Italian coast, where karstic water flows directly into the sea under pressure.

In view of the above, it cannot be claimed that direct groundwater discharge into the world ocean, bypassing the river systems, is a negligible item in the continental water balances. But it is undoubtedly much smaller than the amount drained by rivers from the groundwater reservoir. There is no way yet, ho-

wever, of assessing this item of the water balance. This explains why groundwater discharge calculated according to the amount drained by rivers is somewhat less than total groundwater discharge.

Thanks to recent scientific advances we have now obtained, for the first time, figures on renewable groundwater stores. The reader should bear in mind that the figures are probably an underestimation. For the earth as a whole this amounts to about 12,000 cubic kilometres annually, or slightly less than one-third of total streamflow, which includes both the surface runoff and 11 per cent of the precipitation falling on the land areas.

It is extremely important to have abundant groundwater storage, particularly renewable storage, the most valuable of all water resources. The geographic distribution of groundwater and its renewal rate are connected with geological structure and geographical zonal features. Both factors are so closely intermeshed that often the specific influence of each cannot be distinguished. The role of geographical zonal features used to be underestimated; everything connected with the groundwater regimen was associated for the most part with geological structure. Now, however, it has been established that climate, soil, topography and vegetation all considerably influence groundwater discharge. The closer the groundwater is to the surface, the stronger the influence. Geographical zonal factors have little noticeable influence on deep-lying groundwater. At the other end, soil moisture depends to the greatest degree on these factors.

Geological structure has a noticeable influence on the local hydrologic cycle and water balance. The great role of karst is illustrated by a comparison of the water balances of two river basins near the city of Savona, Northern Italy. The surface of the Letimbro river ba-

sin is 15 per cent karst, while that of the Sansobia river is entirely karstic. In karstic regions the mountain rock (usually limestone or gypsum) presents a chaotic surface relief, with swallow-holes, underground channels and caverns in which water percolating from the surface freely circulates.

TABLE 3

ANNUAL STREAMFLOW AND EVAPORATION IN BASINS OF LETIMBRO RIVER (SLIGHTLY KARSTIC) AND SANSOBIA RIVER (COMPLETELY KARSTIC)

Item	Letimbro River up to Piccardo	Sansobia River up to Eller
Basin area, sq km	33	41
Average elevation of basin, m	404	500
Karstic part of basin, %	15	100
Atmospheric precipitation, mm	1,360	1,376
Total streamflow, mm	744	950
Evaporation (precipitation minus streamflow), mm	616	426

When territory is completely karstic, percolation of water is much quicker, less water remains in the upper strata of rock, and evaporation losses are smaller. This contributes to greater streamflow, chiefly owing to stable groundwater discharge. In the example above, where the two river basins are similar in all respects except in the permeability and water-retaining properties of the rock, streamflow in the completely karstic Sansobia basin is 200 millimetres greater and evaporation almost 200 millimetres less than in the Letimbro basin, which is only 15 per cent karstic.

Many other rivers in Italy show similar features. Annual streamflow of the Nera and Anio rivers, whose

basins are about 80 per cent karstic, is almost 300 millimetres greater than the streamflow typical for the local zonal conditions. On the other hand, the Trigno and Tiber rivers, whose basins are only 20 per cent karstic, have a streamflow close to the zonal figure.

Some rivers of the Soviet Union follow a similar pattern, as shown in Table 4.[8]

TABLE 4

INFLUENCE OF KARST ON WATER BALANCES OF OKA AND UFA RIVER BASINS

Item	Oka River up to Kaluga	Ufa River up to its mouth
Basin area, sq km	54,000	52,850
Annual precipitation, mm	575	550
Annual average moisture deficit, mm	2.20	2.30
Annual streamflow, mm	183	274
Evaporation (precipitation minus streamflow), mm	392	276

The more karstic Ufa basin has almost 100 millimetres more streamflow and nearly 120 millimetres less evaporation, although in all other respects the two basins are very similar.

Karstic phenomena intensify groundwater recharge and groundwater drainage by rivers. Rivers therefore become more aquiferous, and evaporation losses drop.

Permeable volcanic tuffs have just about the same influence on the water balance, particularly on the lithogenous arc of the hydrologic cycle. The Armenian Plateau, which consists of tuff, has practically no surface streams since during precipitation and

snowmelt all the water quickly percolates into the ground and forms plentiful sources of groundwater.

With a different geological structure, such as loose Quaternary deposits, and poor soil permeability, moisture would accumulate in the soil and much larger amounts would be lost in evaporation in dry weather. Groundwater recharge would be less, rivers would carry less water, and surface runoff would play a big part in the regimen of rivers.

Since geological factors usually influence the water balance of comparatively small areas, their influence is felt chiefly on small rivers. The geological structure in large river basins is more diverse and hence its role in the hydrologic cycle is harder to determine.

SOIL

The soil is part of the lithogenous arc of the hydrologic cycle inasmuch as soil water is connected with the uppermost layer of the earth's crust. Yet there is every reason to classify soil water (or soil moisture, as it is more commonly called) separately.

A number of features distinguish soil moisture from groundwater. For one thing, soil moisture is much more closely connected with biological processes. The topsoil, where soil moisture occurs, is not a purely mineral mass but contains varying amounts of humus, a material formed by the partial decomposition of vegetable or animal matter.

Secondly, soil moisture is associated with weather to a greater degree than groundwater. Infiltration enriches the soil with moisture during rains or snowmelt, but in dry weather soil moisture quickly evaporates. The moisture content of the soil is unstable over the greater part of the world's land area. Soil moisture is lost not only through evaporation from the surface

but also through transpiration, one of the vital functions of plants; the moisture is absorbed by the roots.

Since soil moisture is an important factor in plant life, evapotranspiration from the land mass cannot be regarded as a wasteful process. In the hydrologic cycle, it supplies the atmosphere with moisture. From this viewpoint evaporation from the seas is also important. But evapotranspiration from land is beneficial since it plays a definite role in plant life, in the building up of plant matter.

In places where the soil is fertile but lacks moisture, and the climate is warm, farmers build irrigation networks to supply the fields with sufficient water for crop growth.

Soil moisture carries out another important function by percolating deep underground to recharge groundwater. This item of soil moisture loss ranks second after evapotranspiration. Groundwater recharge goes on most intensively in places where the soil is more than sufficiently moist, particularly in forests, where the topsoil is made friable by the root systems of the trees and therefore is highly permeable. Groundwater is also abundantly recharged beneath lakes, reservoirs and rivers. Places where soil moisture and surface water percolate deeply and recharge groundwater were named *potuskuls* by the eminent soil scientist and hydrologist G. Vysotsky. There are fewer potuskuls in arid regions and the amount of water passing through them is not great. Consequently, renewable groundwater stores there are less than in regions that get sufficient moisture, where potuskuls cover a large area and are highly permeable. Groundwater zonality is connected chiefly with this.

Although there is not much soil moisture (see the opening chapter) it is quickly replaced and, as we have seen, is important in the hydrologic cycle, in biolo-

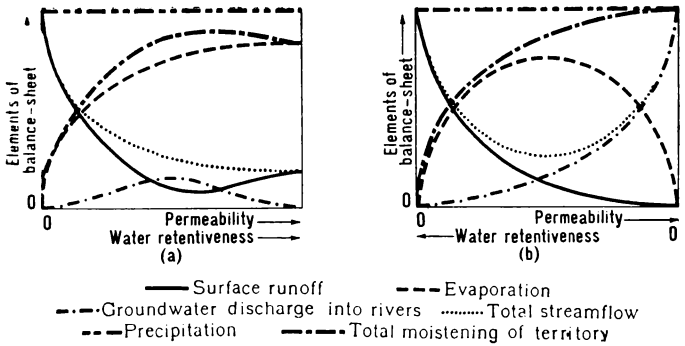


Fig. 2. Theoretical curves showing the dependence of elements of the water balance on permeability and water retentiveness of the soil: (a) permeability and water retentiveness change in the same direction, (b) permeability and water retentiveness change in opposite directions

gical processes and in economic life. The soil not only influences the formation of groundwater but also the rate of streamflow and the regimen of rivers. Many hydrometeorological processes are linked up with it. The soil is an intermediary between *climate and meteorological factors, on the one hand, and the hydrological regimen of groundwater, rivers and lakes, on the other.*

How the soil cover influences the hydrologic cycle and the water balance in highly diverse and essential ways can be judged from curves compiled by the present writer (Fig. 2).[9] They show the dependence of elements of the water balance on soil permeability and water retentiveness.

These two properties influence the elements of the water balance by operating together, not separately, as the curves indicate. The graph on the left shows

how water-balance elements change when soil permeability and water retentiveness increase or decrease simultaneously. The graph on the right shows the changes when permeability increases and water retentiveness decreases, or vice versa. Both cases occur in nature.

Let us see how water balance elements change depending on those two properties of the soil. First, the case when permeability and water retentiveness change in the same direction. When both permeability and water retentiveness are small, most of the precipitation goes into surface runoff. There is little or no soil moisture and therefore little water evaporates or goes into groundwater. Streamflow is fed chiefly by surface (flood) runoff. In the periods between flood runoffs the streams dry up since they receive very little groundwater.

Good permeability and water retentiveness radically change all the elements of the water balance. Surface runoff is reduced but evapotraspiration increases. Groundwater discharge into streams reaches its maximum not at highest permeability and water retentiveness but at their optimal (median) values.

When the two properties change in opposite directions, all elements of the water balance likewise undergo considerable alterations. In this case, as the graph on the right shows, surface runoff drops sharply and groundwater discharge into rivers rises abruptly. There is little evaporation when the two soil properties are at their extremes but it reaches a maximum when permeability and water retentiveness have median values. On the other hand, total streamflow changes in the opposite way. It is greatest when permeability and water retentiveness have extreme values and least when they have median values.

The author charted all these sharp changes in water

balance elements against a background of similar climatic conditions. Atmospheric precipitation was taken as invariable in all cases. This was done to show more clearly the part the soil cover plays in the water balance and to give a better idea of the factors that shape the water balance-sheet.

Until recently many scientists believed that climate, and atmospheric precipitation in particular, was the chief factor in the hydrologic regimen and water balance, and underrated other factors, especially the groundwater and the soil. In today's comprehensive approach importance is attached to all the factors involved.

The soil cover, as we can see, is a kind of arena in which many processes of the hydrologic cycle interact: soil moisture, formed in the process of infiltration, goes into evaporation and transpiration and is used to recharge groundwater.

An important point to bear in mind is that the water balance is affected not only by the natural hydrophysical properties of the soil but also by the changes man introduces into these properties when he cultivates the soil, plants trees, drains marshland, and so on.

It is difficult to overestimate man's potential for altering the hydrophysical properties of the soil and thereby changing the water balance to suit his needs. We shall deal with this later in the chapter "Controlling the Hydrologic Cycle".

Besides theoretical studies, experimental investigations of the role of the soil cover in the water balance are carried out. They are conducted on plots of land ranging from half a hectare to one hectare in size, situated on hillsides. A ridge is built up around the plot to separate it from the surrounding slope. A gutter is laid at the lower end to catch surface runoff

from the plot during rain or snowmelt. Observations of elements of the water balance, such as precipitation, snow cover and soil moisture, are carried on at the plot. The permeability, minimum and maximum moisture capacity and other hydrophysical properties of the soil are studied.

Since the results of the experiments depend greatly on a correct choice of site, the plots (which are laid out in groups in one place) should be similar to one another in all respects except for the hydrological property to be studied. For example, if the purpose is to discover how forest and ploughland (autumn ploughed) affect streamflow, as compared with meadowland, sites are chosen on all three types of land. The three plots must have a similar type of soil, similar gradients and topography, the same exposure and the same size. An effort should be made to select plots that are close to one another, so that climatic conditions are similar for all three.

In brief, the selection of experiment plots is a fairly complicated and important matter, but it is worth the effort for, as Alexander Herzen, the distinguished nineteenth-century Russian democrat said, "Method is the embryology of truth". If the method used is correct it is not difficult to obtain correct, theoretically-substantiated findings. But if insufficient attention is paid to the method of investigation and if the choice of the object of experimental study is not a happy one, no amount of effort will produce substantiated results.

Unsuccessful experiments are, unfortunately, no rarity. This explains why experiments sometimes lead to "contradictory" conclusions. But when you carefully examine the method used in obtaining the data you find that actually there are no contradictions at all.

For instance, there are many types of ploughland,

and when you compare the water balance of areas that were cultivated in different ways the results will be contradictory. The same applies to forestland, which differs depending on the type of stand, its age and vigour, and type of exploitation. It is important, for example, to know whether cattle are pastured in the forest. If they are, the soil cover will be more packed down and will have lost some of the high permeability of natural forest soils. These points play a big part in the local hydrologic cycle and the shaping of a water balance.

The influence of soil cover on water balance elements in line with the theoretical patterns shown in Fig. 2 can be illustrated by several examples based on experimental findings.

Observation of spring surface runoff from tracts of land in the mixed forest zone of the European part of the Soviet Union in a district having a uniform climate has shown that the runoff coefficient, that is, the relation of volume of runoff to the volume of precipitation or snow cover producing the runoff, ranges between 0.01 and 0.53 depending on the type of the tract and soil. This is illustrated in Table 5.

TABLE 5

SPRING RUNOFF COEFFICIENT IN MIXED FOREST ZONE [10]

Soil	Type of Land		
	Pasture and fallow land	Ploughland (autumn ploughed)	Forest
Loam	0.53	0.39	0.19
Sandy loam	0.33	0.23	0.03
Sandy	0.20	0.10	0.01

The hydrophysical properties of the ground cover are determined by the type of field and the structure of the soil. Meadow soils are less permeable than ploughland and much less so than forest soils, which are capable of absorbing a vast amount of water. When the soil is sandy loam, the rate of runoff from meadowland and fallow land is eleven times greater than from forestland; it is 20 times greater when the soil is sandy.

The data in Table 5 fully agree with the theoretical curves in Fig. 2. Sandy loam in meadowland and idle land most closely correspond to the left part of graph (*a*), where surface runoff is high when permeability is low. Forest surface runoff, particularly from sandy soils, corresponds to the right part of graph (*a*), where permeability is high and the runoff is very low.

The effect of all other factors of spring runoff has been eliminated from the above data, so that the coefficient rather accurately characterizes the role of ground cover in the water balance. Since Bass obtained the findings presented in Table 5 from experiments conducted at 14 sites, they may be considered trustworthy.

All elements of the water balances of forests differ substantially from those of fields. There is a great deal of surface runoff on meadowland and very little in forests. Evapotranspiration, especially transpiration, is greater in forests.

Since forests lose little water through surface runoff, the total moisture content of their soil is greater. Significantly, subsoil and groundwater flows in forests, taken together, amount to twice as much as in fields. Subsoil flow, which forms in the lower layers of the soil, is the most typical flow in forests, while fields, which lose much water in surface runoff, have practically no subsoil flow.

The chief differences in the water balances of a forest and an adjacent meadow are due to the soil, which in the forest has high permeability and water-regulating ability. The differences in the water-balance properties of forest and field soils are connected with biogenetic processes. Forest soil is better structured and more permeable due to the action of the root system of the trees and greater enrichment of the soil by the humus resulting from leaf decomposition.

In the section "Reshaping the Local Water Balance" an example relating to the forest-steppe zone will be cited. The structure of the water balances of separate tracts there is just as diversified as in a forest zone.

RIVERS

Rivers have been studied more thoroughly than the other parts of the hydrologic cycle. At the dawn of civilization, man settled on the banks of rivers, sailed down rivers to explore unknown lands, drank river water and ate fish caught in rivers. As productive forces developed, man began to use river water for irrigation and then as a source of power, from primitive water mills to modern hydropower plants with capacities of five million kilowatts.

Many ancient civilizations were inseparably bound up with rivers—ancient Egypt with the Nile, Assyria and Babylon with the Euphrates and the Tigris, and India with the Indus and Ganges.

Man's dependence on the regimen of rivers—he was at the mercy of floods but he also used flood waters to irrigate his fields—stimulated a study of their regularities. Observations of the levels of the Nile were recorded in ancient Egypt in the 20th century B.C. An ancient Nile gauge is preserved at As-

wan, and a Nile measuring instrument of a later period exists on Roda island within the bounds of Cairo.

The instruments were in the possession of the priests, who predicted what kind of harvest should be expected. The connection between harvests and the levels of the Nile was not accidental. When the river was at high flood, large areas were inundated and the water remained on the land for a longer time, which meant a better harvest than when the flood was low. An annual record of the height of the Nile floods has been kept in Cairo starting with the Mohammedan period, so that there is a record of the river's rise and fall for some twelve centuries.

The history of Russia was closely linked with her rivers, first with the Dnieper and then with the Volga. The famous route "from the Varangians to the Greeks" ran down the Western Dvina and the Dnieper. Yermak's voyages down the Tobol and Irtysh rivers of Siberia and those of Poyarkov and Khabarov down the Amur near the Pacific seaboard played an important part in Russia's development. One of the Russian government's first geographical publications, compiled early in the seventeenth century, was largely devoted to detailed description of the country's rivers.

The St. Lawrence and Mississippi rivers and Great Lakes played a big role in the development of North America, as did the Parana, Paraguay, Uruguay and Amazon rivers in the settlement of South America. Although all of Africa's large rivers have numerous rapids and waterfalls, the Nile, Niger, Congo, Zambezi, Orange and other rivers play an important part in the life of the continent.

The use of rivers for navigation, as a source of drinking water, for irrigation, and later for hydraulic power were the first steps in water management and also in the development of productive forces.

Naturally, rivers and, in part, lakes have been studied more thoroughly and comprehensively than the other parts of the hydrologic cycle.

The establishment of a large-scale network of hydrologic stations on rivers and lakes in Europe and the United States began in the last quarter of the nineteenth century. Today streamflow observations are made at about 20,000 hydrologic stations all over the world. One-quarter of them are in the Soviet Union.

In the hydrologic cycle, rivers return to the seas the water which the atmosphere carries from the seas to dry land in the form of vapour. The seas lose by evaporation more than they gain in precipitation, the difference corresponding to the annual discharge of the rivers into the seas.

Rivers are fed by surface runoff and groundwater discharge. *Surface runoff*, which flows overland into streams, is divided into *snowmelt runoff* and *rainfall runoff*, with *mountain snowmelt runoff* (from the melting of permanent snow) and *ice runoff* forming a separate group.

The difference between snowmelt runoff on the plains and in the mountains is that the former usually occurs in spring and the latter in summer. (Snowmelt runoff in the Far North also takes place in summer.) The mountain feeding of rivers is often called alpine, after the rivers of the Alps, the first to be studied in this respect.

On the fringes of the ice sheets of Greenland and Antarctica rivers flow in channels of ice. They appear during the brief polar summer and are fed by surface ablation. Since these rivers form in the same channels year after year they may be considered permanent and similar to rivers that flow through arid steppeland, semi-deserts and deserts and are fed during

short periods by snowmelt and heavy rainfall. In the periods between snowmelt and rainfall the rivers of those regions dry up because they get little or no replenishment from groundwater.

All types of surface runoff form floods, the duration of which may vary considerably. On large rivers like the Volga and the Ob the spring floods due to snowmelt last three or four months because the melting period occurs at different times in different parts of the basin, coming earlier in the southern areas and later in the northern.

Mountain rivers likewise have long flood periods. Although these rivers do not have a large drainage basin, flood flow lasts for some time because snowmelt occurs first in the lower part of the basin, gradually spreading higher and higher until in the middle or the second half of summer, permanent snow begins to melt in the highest parts of the mountains.

Prolonged floods are typical of tropical rivers as well, particularly equatorial rivers flowing through the rain forests, where long, heavy rains are frequent. On rivers like the Amazon and the Congo and their tributaries, one flood follows another over a large part of the year.

Floods of short duration, lasting a few days or even only a few hours, are caused on small rivers in mountains and on plains by storm rainfall. The streams in the Sahara and Kalahari deserts are typical examples. Such streams have a dry rocky or sandy channel in which an intensive cloudburst brings about a turbulent flood of short duration once a year, or once in several years.

The Soviet Union has rivers in the area east of the lower reaches of the Volga and in northern Kazakhstan that are fed only in spring during snowmelt. For the remainder of the year they have practically

no flow and are divided into pools between which the channel remains dry for nine to eleven months of the year.

As far as man is concerned, surface runoff does more harm than good. First of all, it means an irretrievable loss of water for agriculture. This is particularly felt in regions insufficiently supplied with moisture. Secondly, surface runoff washes away topsoil, creating erosion scars and gullies. In the mountains, surface runoff creates dangerous mud-laden torrents. Soil erosion causes tremendous economic losses; the most effective method of erosion control is to reduce or eliminate surface runoff. Thirdly, surface runoff leads to floods; rivers overflow their banks and inundate the surrounding territory, causing great damage. Finally, surface runoff cannot be utilized for most economic needs unless it is regulated by costly reservoirs or land improvement.

Snowmelt floods on mountain streams are an exception. Their water is used to irrigate arid regions adjoining the mountains. These floods are a boon because they occur in the vegetation period when water is most needed for irrigation. The benefits resulting from floods on mountain rivers can be clearly seen in Central Asia, in the western areas of the United States and in a number of other regions.

Groundwater plays an exceptionally important part in the feeding of rivers because it provides stable streamflow resources, maintaining them in the periods between flood runoffs. These resources are most valuable from the economic point of view.

Different types of groundwater feed rivers in different ways. The most stable feeding is by artesian waters and groundwater that comes from the deepest of the layers drained by streams.

Streams in the permafrost regions of Central and

Eastern Siberia are fed chiefly by alluvial groundwater, which is depleted so rapidly in winter that shoals form on many rivers, including big ones. The movement of groundwater in the debris types of deposits common in mountains and also in gravel-boulder alluvial deposits is often turbulent. The most widespread type of groundwater moves through the rock mass in a slow laminar flow. The velocity of laminar flow in close-grained rock is only one-fifth of a metre a day, and often less. Turbulent groundwater flow in coarse debris or in boulder beds of alluvial origin is much more rapid, often several hundred metres an hour and several kilometres a day.

Some types of karst groundwater quickly dry up after rainfall or snowmelt ceases. On the other hand, there are powerful karst water springs with a fairly stable yield.

The feeding of rivers is subordinated to geographical factors.[11] For the most part, glaciers feed the streams in the polar and high mountain regions; snow feeding predominates in the temperate zones with the exception of certain regions and latitudes; rain predominantly feeds rivers in the tropics and the low latitudes, up to about 40° to 45° N and S. Most of the world's rivers are fed by rain.

There are comparatively few rivers fed primarily by groundwater. These lie in the main in arid regions adjoining the flysch zones of mountain massifs. Rainwater and snowmelt easily percolate deep into the ground where the friable flysch deposits are extensive, forming an abundance of groundwater that tapers out in the foothill belt and gives rise to rivers with a regulated flow of groundwater origin. In Central Asia and Transcaucasia, where such rivers are common, they are called *kara-soo*, which means "black water".

The type of the river regimen depends not only on

the source of nourishment but also on the seasonal periodicity of streamflow. Rivers fed predominantly by snowmelt runoff are replenished in summer if they lie in the subpolar regions, where the snow melts late, and in spring if they are in the temperate latitudes. Taken by itself, the source of feeding would not enable us to differentiate the regimen of the Volga and the Anadyr. For the most part, both rivers are fed by snow water, but the Volga gets mainly spring runoff, while the Anadyr gets summer runoff.

An analogous example is provided by the Orinoco and the Mekong. Both are fed almost exclusively by rain, but the Orinoco is a typically equatorial river with an abundant discharge throughout the year, and somewhat more plentiful in autumn. The Mekong is a tropical river which is fed chiefly in summer by monsoon rains and has a very low winter discharge.

A knowledge of the seasonal periodicity of streamflow is of practical as well as theoretical importance. A steady discharge throughout the year would be ideal for practical purposes. However, few rivers have this. Therefore, in assessing the possibility of using rivers we must either guide ourselves by the season when the water is lowest or by prospects of regulating the flow.

To avoid a subjective appraisal of streamflow from different sources, with allowance for seasonal variations, we have adopted the following scale:

"almost exclusively"—over 80 per cent of annual discharge;

"predominantly"—50 to 80 per cent of annual discharge;

"largely"—under 50 per cent of annual discharge.

Thus, we obtain 12 gradations for the four sources of feeding and 12 gradations for the four seasons of the year.

If all combinations of these gradations were found in nature we would have 144 types of river regimen. In reality, there are only 38 (see Table 6), because

TABLE 6

REGIMEN OF THE WORLD'S RIVERS

Sources of feeding	Streamflow by seasons											
	Spring			Summer			Autumn			Winter		
	80%	50-80%	50%	80%	50-80%	50%	80%	50-80%	50%	80%	50-80%	50%
Snow 80%	×											
50-80%		×	×	×	×	×						
50%			×		×	×						
Rain 80%				×	×	×		×	×		×	×
50-80%			×		×	×		×	×	×	×	×
50%			×	×	×	×					×	×
Glaciers 80%				×								
50-80%				×	×							
50%					×	×						
Ground-water 80%												
50-80%						×						
50%			×			×						

some combinations are impossible, such as snow or glacier feeding in autumn and winter, and some simply do not exist in nature.

The volume of average annual discharge is a key factor in determining a river's water resources. Streamflow records are kept at about 20,000 stations, as mentioned above.

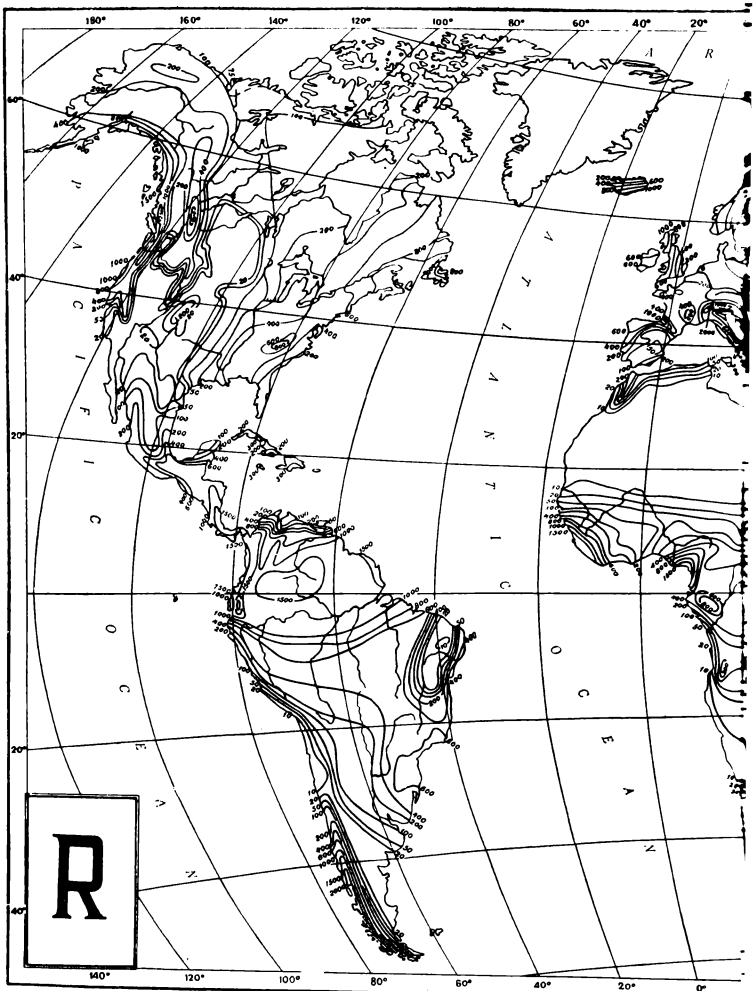
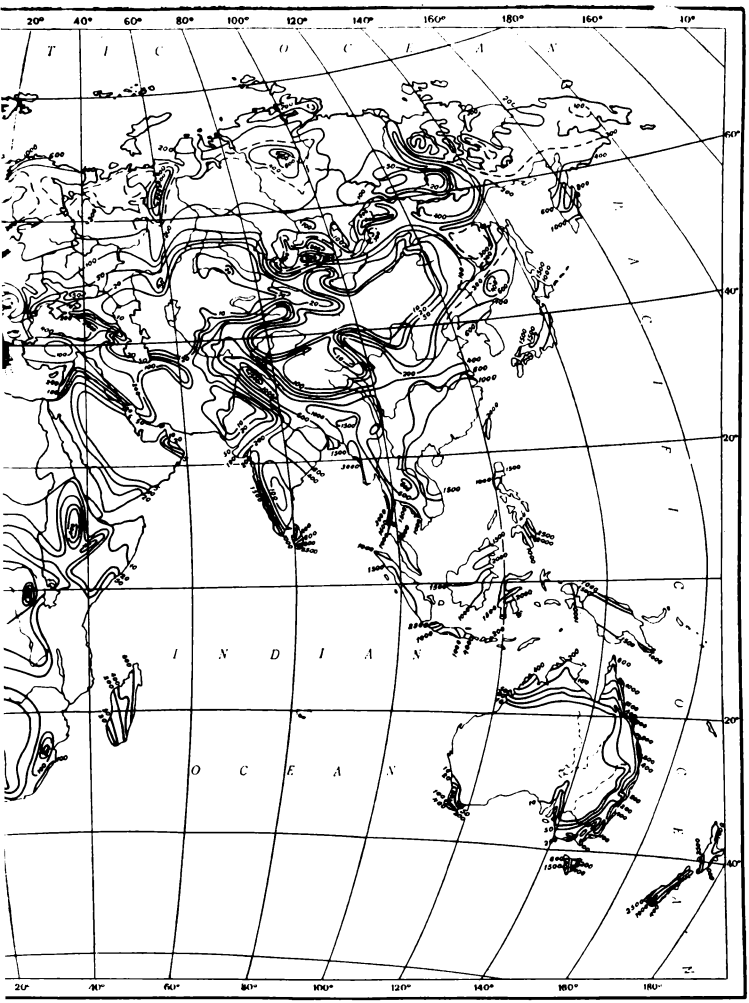


Fig. 3. The flow of the world's rivers. (The fi



gures denote annual streamflow in mm of depth)

Gauging stations on the Neva, Northern Dvina, Western Dvina, Neman, Dnieper, Don, Volga, Ob, Lena, Amur, Syr Darya, Amu Darya, Kuban and other rivers in the Soviet Union have flow data for the past 70 to 80 years, and on some control sections for as much as 100 years. Similar data is available for rivers in all European countries, a number of countries in Southeast Asia, in Africa (the rivers of Algeria, the Nile, the Niger and part of the Congo), in the United States, Mexico and part of Canada, and in South America, for some of the rivers of Brazil, Argentina, Chile, Venezuela and other countries.

However, the flow data for many rivers in Africa and South America is insufficient. In a number of fairly large regions there is no data at all. Approximate estimates of the discharge of the rivers of these regions are made on the basis of precipitation records, which are compared with data for analogous rivers whose average annual flow is known.

Gauging station data and approximate data obtained through interpolation were used to compile maps of the flow of the world's rivers. The first map was compiled from data up to 1940 and was published in 1945.[7] A revised map appeared in 1960.[12] Further clarifications led to a third edition of the map.[11b]

The world map of streamflow in Fig. 3 represents a final revision. It was made by Dreier, Karasik, Nikolaeva and Chernogaeva of the Institute of Geography of the USSR Academy of Sciences, working under the guidance of the present writer. Although each of the successive maps was more precise than the one before it, the revisions have not basically changed the summarized data on streamflow by continents and for the world's land surface as a whole.

The streamflow map is compiled in terms of millimetres of depth, calculated by dividing the average

annual runoff by the area of the drainage basin. Hydrologists often express river runoff in terms of litres per second per square kilometre of the drainage basin. This is convenient for engineering calculations, but we prefer to use millimetres of depth because this can be compared with atmospheric precipitation, which is expressed in the same terms.

Annual volume is obtained by multiplying average discharge in cubic metres per second by the number of seconds in a year (31.5 million). For example, the Volga has an average discharge of 8,100 cubic metres per second, which makes the annual runoff equal to

TABLE 7

*ANNUAL RUNOFF OF THE WORLD'S RIVERS**

Region	Volume, km^3	Depth, mm
Europe	3,110	319
Asia	13,190	293
Africa	4,225	139
North America	5,960	287
South America	10,380	585
Australia**	1,965	226
Greenland	700	180
Antarctica	2,200	250
Total	41,730	280

* New data of the Institute of Geography, USSR Academy of Sciences.[13]

** Including Tasmania, New Guinea and New Zealand. The figures for Australia alone, without the islands, are 410 km^3 and 47 mm.

256,000 million cubic metres. To avoid using such astronomical figures the discharge of large rivers is expressed in cubic kilometres.

The distribution of annual streamflow by continents is shown in Table 7.

Total annual flow of all the rivers of the world, including polar glacial flow, is 41,730 cubic kilometres. Our previous estimates put it at 38,200 cubic kilometres.[14] The increase of nearly 3,000 cubic kilometres is due in the main to new data on the Amazon river, whose flow had not previously been measured and was estimated at about 3,500 cubic kilometres annually. Measurements at the town of Obidos on the lower reaches of the Amazon in the sixties showed annual runoff there to be 5,000 cubic kilometres; at the mouth of the river it was estimated at 6,000 cubic kilometres, or 2,500 cubic kilometres more than previously thought. The figure for total river flow for South America was increased correspondingly.

European streamflow has been increased by 160 cubic kilometres by clarifications and the inclusion of data for Iceland. New data have increased the figure for Asia by 340 cubic kilometres and for North America by 560 cubic kilometres. On the other hand, the African total has been reduced by more than 300 cubic kilometres.

We must remember that all river flow does not reach the world ocean. Some 32,000,000 square kilometres of land does not send any water into it. This land is either desert of the Sahara or Kara Kum type, or the basins of rivers such as the Volga, Ural, Kura, Syr Darya, Amu Darya and others which do not empty into the open sea.

When these river basins and desert regions are loosely called drainless, the term relates exclusively to the ocean. Local streamflow occurs everywhere, al-

though in some deserts it is rare and the amount of discharge is very small.

The flow of all inland rivers in drainless basins is about 730 cubic kilometres, or 23.8 millimetres of depth. The basin of the Caspian Sea, with the Volga, Ural, Kura and other rivers, covering an area of about 1,800,000 square kilometres, accounts for about 300 cubic kilometres of that amount.

Consequently, annual river discharge into the world ocean is 41,000 cubic kilometres. Besides river water this includes ice and the products of ablation from polar glaciers. In previous studies (1945 and 1960) we estimated the amount of water coming from polar glaciers at 1,800 cubic kilometres a year. Investigations in the Soviet Arctic regions and in Antarctica in the past decade have enabled us to arrive at a more exact figure.

The Antarctic icecap discharges 2,200 cubic kilometres annually[15]. The prominent glaciologist F. Löve estimates, on the basis of the latest data, that annual discharge from the Greenland icecap is 440 cubic kilometres. The small polar glaciers in the Arctic islands of Eurasia and North America furnish 270 cubic kilometres. Thus, annual flow from all polar glaciers into the ocean is 2,900 cubic kilometres.

Mountain glaciers account for about 200 cubic kilometres. Hence, total flow from all glaciers of the world amounts to 3,100 cubic kilometres. But since the 200 cubic kilometres from mountain glaciers and the 270 cubic kilometres from small polar glaciers are classified as part of continental streamflow, we include in our estimates only the 2,900 cubic kilometres a year from the ice sheets of Antarctica, Greenland and the Canadian Archipelago.

Only a small part of this water is the result of glacial ablation, which forms streams at the outer

edges of glaciers during the brief polar summer. The chief mass of glacial ice reaches the ocean in the form of icebergs. Latest estimates put the total annual volume of the icebergs carried into the ocean at about 1,880 cubic kilometres. As Soviet investigators in the Antarctic have learned, a substantial amount of snow there is blown into the ocean. Snow transfer and ablation account for a little more than 1,000 cubic kilometres annually. In future, polar glaciers will be an important source of water.

Asia has more streamflow than any other continent (32 per cent of the world total), followed by South America (25 per cent), North America (14 per cent), Africa (10 per cent), Europe (7.5 per cent) and Australia, not counting the islands (one per cent). Water resources cannot, however, be judged entirely by streamflow. The amount of streamflow per unit of continental area, expressed in terms of depth, gives a more correct picture. Judging by streamflow depth, South America is richest in river water resources (585 millimetres), followed by Europe (319 millimetres), Asia (293 millimetres), North America (287 millimetres), Africa (139 millimetres), and Australia, not counting the islands (47 millimetres).

Now let us examine several more points to round out the picture of river water resources.

First, the geographical distribution of streamflow is extremely uneven. Populations and industries are usually concentrated in places where there is a water supply. Often, however, water has to be delivered to towns, factories, mills and irrigated land.

Second, the volume of streamflow is distributed unevenly in time. There are both seasonal and annual fluctuations. In low-water years many rivers discharge only one-half or one-third as much water as the average, while in high-water years they discharge between

one and a half and two times the average. Streamflow in many rivers is only one-third to one-fifth as much in low-water years as in high-water years. Such unevenness complicates water use. Calculations have to be based on the figures for low-water seasons and low-water years.

Discharge varies less in large rivers than in small ones. Similarly, the larger a river-system area the more stable the average discharge. That is because some rivers in the area will have a small discharge in some years while others have a big discharge. It has been observed in the Soviet Union that when the discharge is low on the rivers of the European part of the country, the rivers in Central Asia or the Soviet Far Eastern regions have a high discharge.

In the world as a whole, streamflow does not vary greatly from year to year. We can regard it as stable since high discharge in some areas compensates for low discharge in others.

Third, rivers in the temperate and frigid zones are icebound for several months a year. The ice cover, the spring and autumn ice movements and the formation of ice and sludge in the water have to be taken into account in planning the use of river water resources.

Fourth, it is important to know the amount of sediment transported by rivers, a process that has been studied fairly thoroughly in the Soviet Union. G. V. Lopatin, a hydrologist who is an expert on sediment and has compiled sediment maps[11c] of the rivers of the Soviet Union, has calculated that they contain an average of 130 grams of sediment per cubic metre of water.[16] With a total discharge of 4,350 cubic kilometres annually, the rivers of the Soviet Union carry 594 million tons of sediment. Annual erosion per square kilometre of the territory of the

Soviet Union averages 28 tons. The territory is lowered by approximately 0.02 millimetre every year through erosion.[17]

Rivers also carry dissolved substances. In the Soviet Union these amount to 384 million tons annually. Including organic substances, mineral colloids, trace elements and inorganic biogenic elements, the total is 486 million tons.[18] Sediment plus the substances dissolved in the water add up to almost 980 million tons annually. Erosion averages 45 tons per square kilometre, with an annual erosion depth of about 0.02 millimetre. In Soviet Central Asia, annual erosion depth is 0.05 millimetre, while in the northern regions of the European part of the Soviet Union it is only 0.06 millimetre.[17]

World river sediment yield is roughly estimated at 14,000 million tons a year. Besides, more than 2,500 million tons of dissolved substances are carried by the rivers to the sea.[18] Counting the dissolved substances transported by the world's rivers in inland "drainless" areas, we get a total of something like 3,000 million tons a year. Aggregate yield of all products of erosion reaches 17,000 million tons, and depth of erosion is about 0.075 millimetre annually.

Actually, though, the changes in the surface of the world's land area may not follow the above pattern because of the operation of another powerful factor, tectonic movements. Tectonic processes cause some parts of the land to rise and others to sink. Only lowering, however, is caused by the transfer of sediment and dissolved substances to the sea by rivers. In terms of geological time, this process takes place fairly rapidly.

We must remember that the above figures on the transfer of erosion products refer only to the past three or four decades. They cannot be applied to lon-

ger periods because erosion processes are due in large part to man's activities, the nature of which changes substantially in time. In the remote past, erosion intensity was probably quite different owing to the different climate and more turbulent tectonic processes.

LAKES AND RESERVOIRS

Lakes and rivers are inseparably linked up within the hydrologic cycle. Very few lakes are independent of rivers; rivers usually flow into, from or through them.

A characteristic feature of lakes is that more water is evaporated from their surface than from the surrounding land. Evaporation from lakes goes on all the time, but on the surrounding land there are periods when the topsoil is dry and has no moisture to lose by evaporation.

The Caspian Sea annually loses a layer of almost one metre of water through evaporation. In its coastal areas, mostly arid land, all the water that falls in precipitation—between 200 and 300 millimetres—evaporates, from one-fifth to one-third as much as from the surface of the Caspian. In the North and the equatorial zone, where the soil is almost always moist, there is less difference between the amount of evaporation from land and lakes.

The main role drainage lakes play in the hydrologic cycle consists in regulating streamflow, making it more even during the year. For example, the flow of the Neva river, on which the big city of Leningrad stands, is well regulated by a system of lakes, including two of the largest in Europe, Lake Ladoga and Lake Onega. Siberia's Angara river is almost ideally regulated by Lake Baikal, the deepest lake in the world and the largest in Asia. The St. Lawrence ri-

ver in North America, which is regulated by the Great Lakes, is another classical example.

A much greater role in regulating streamflow, however, is played by storage reservoirs, man-made lakes. There are now about 1,350 reservoirs in the world with a capacity of more than 100,000,000 cubic metres each. The Soviet Union has 150 large reservoirs of this size. The total capacity of all the big reservoirs in the world is somewhat more than 4,100 cubic kilometres. Those in the Soviet Union have an aggregate capacity of 810 cubic kilometres.[19]

A rough estimate of the streamflow regulated by these reservoirs is given in Table 8.

TABLE 8

STABLE STREAMFLOW BY REGIONS
(IN CUBIC KILOMETRES)

Region	Natural	Reservoir-regulated	Present total	Increase (per cent)
Europe	1,125	200	1,325	18
Asia	3,440	560	4,000	16
Africa	1,500	400	1,900	27
North America	1,900	500	2,400	26
South America	3,740	160	3,900	4.2
Australia*	465	35	500	7.5
All land**	12,170	1,855	14,025	15

* Including Tasmania, New Guinea and New Zealand.
** Excluding Antarctica and Greenland, where there are no reservoirs.

The regulation of about 1,855 cubic kilometres of streamflow by reservoirs is a tremendous achievement

that has increased the world's stable streamflow by 15 per cent.

In the Soviet Union reservoirs regulate at least 320 cubic kilometres of streamflow, enlarging the country's stable streamflow resources by approximately 30 per cent.

Regulation increases the supplies of fresh water that are most readily available for use. It also diminishes floods by slicing off their peak and thus reducing the damage they cause.

Lakes and reservoirs are more or less closed ecological systems involving a complex of interconnected mechanical processes (currents, waves, sediment movements), physical processes (thermal and ice phenomena) and chemical and biological processes. In lakes and reservoirs with a high degree of flowage these processes are similar to those in rivers. Big lakes with relatively weak flowage, with large volumes of water in relation to inflow and outflow, such as Baikal, Nyasa, Tanganyika, Victoria, Superior and Michigan, have ecosystems of a specific type. These ecosystems are highly sensitive to man's activities, especially to organic pollution.

BIOLOGICAL ARC

This is a very complex and diverse arc of the hydrologic cycle. We shall only outline the highlights here.

Everybody knows that water is vital to plant and animal life. Plants and animals contain a very high percentage of water. Three-quarters of the human body consists of water, about 40 litres of it.

Human beings drink a considerable amount of water. In the Soviet Union the daily requirements of drinking water per person are taken as three to four litres, a standard evidently based on conditions in

land vegetation and, to a great extent, by sea phytoplankton. If it were not for photosynthesis, human, animal and plant respiration, and especially the burning of coal, oil and other combustible materials, would deplete the oxygen content of the air and produce excessive carbon dioxide, making organic life impossible. As it is, the carbon dioxide content of the air has almost doubled in the past fifty years and is expected to continue to grow in future. For this reason, every effort must be made to increase the amount of vegetation.

Transpiration, an involved process vital to plant life, is one of the most significant biological aspects of the hydrologic cycle. When the roots of plants absorb soil moisture, mineral nutrients enter the plant body with the water. Plant life and plant growth, and thus the harvest, depend on a regular supply of water. In transpiration, moisture is given off into the air by the surface of leaves and other parts of the plant. Transpiration is important in regulating the plant temperature. If it were not for transpiration, plants would die from heat. The heat losses during transpiration lower the plant temperature. Within certain limits this process is regulated by the plants themselves. In hot weather the stomata on the surface of the leaves open wider and help to increase transpiration and reduce the temperature. In cooler weather the stomata do not open up so widely. Thus, transpiration is both a physical and a physiological process. It differs from ordinary evaporation from the surface of non-living substances because it can be regulated to some extent by the plant itself.

The amount of water transpired by different plants varies greatly. In arid regions there are drought-resistant plants which transpire a relatively small amount of moisture.

The transpiration capabilities of plants are often estimated by what we call the *coefficient of transpiration*, characterizing the weight of the moisture given off to form a unit of weight of dry plant substance. For example, it takes from 300 to 500 metric tons, or cubic metres, of water to form one ton of surface vegetation of wheat, that is, grain and straw.

How much water goes for transpiration depends on many factors: the nature of the plant (the degree to which it is adapted for growth with a limited water supply); the weather; the presence of moisture in the soil. In hot, dry weather plants give off a large amount of water. If there is insufficient moisture in the soil the plant will wilt.

Plant roots absorb soil moisture at varying depths. The root system of wheat goes down to a depth of between two and two and a half metres. The roots of an oak tree sometimes reach down to 20 metres. By sending down deep roots plants depend less on moisture variations in the topsoil; moisture supply is more stable at lower levels.

The depth to which roots penetrate often depends on the depth of moisture. On irrigated fields where the soil is well watered, wheat plants send 85 to 90 per cent of their roots to a maximum depth of 40 centimetres, while on a non-irrigated field the roots may reach a depth of two and a half metres. The same holds true for trees. In arid places their roots penetrate to the water table.

There is a connection between transpiration and evaporation from the soil. The floor of a forest may contain a lot of moisture but not much of it evaporates because little sunlight penetrates through the leaves and because the air circulates slowly and is more saturated with moisture. Under these conditions most of the forest's moisture losses are through transpiration.

The ratio between transpiration, which is *productive* use of water, since it is vital to plant life, and evaporation from the soil, which is *non-productive*, changes from season to season, depending on the stages in plant growth.

Before sowing, water losses in a cultivated field are all through evaporation and are non-productive. As the stand of crops develops, evaporation decreases and transpiration increases. Before plants reach the stem extension stage, in which the soil is covered by a solid crop stand, transpiration accounts for only 25 per cent of evapotranspiration. Towards the flowering stage transpiration on a field of wheat, for example, increases to 60 per cent of the evapotranspiration, while evaporation drops to 40 per cent as a result of the shading of the soil by the plants.

How is transpiration measured? There was a time when researchers covered plants with glass jars and measured the transpiration by the amount of moisture inside the jars. But this method was given up since it does not correspond to natural conditions. The air inside the jar does not move and gradually becomes saturated with moisture. Wind, an important factor in evapotranspiration, is of course absent inside a jar.

A fairly widespread method consists in weighing cut stalks of grass plants and tree twigs and estimating transpiration by the weight losses. Cut plants continue to transpire moisture by inertia for some time, as under natural conditions, and this is taken into account. However, the method is imperfect since cut plants behave differently from growing plants. As a result, much unreliable information about transpiration has been published.

The lysimetric method produces the best results but it is cumbersome and therefore limited in use.

The method is as follows. Two blocks of soil are dug up together with growing plants and are placed in metal vessels. The plants in one of the blocks are left intact. In the other, the stalks are cut off right down to the base, are dried, and are then suspended above the soil to simulate its shading by a stand of grass under natural conditions. The vessels containing the blocks of soil are called *lysimetres*. They are weighed and then placed in holes in the ground, amidst the grass stand, so that their soil surface is on a level with the untouched surrounding soil.

After a few days the lysimetres are weighed again, and the difference is registered. The lysimetre in which the plants were left intact shows the amount of evapotranspiration. The other, with the cut plants, indicates only the evaporation. The difference between the weight losses of the first and second lysimetres, with account taken of the water that percolates to the bottom of the lysimetre (into a funnel-like vessel) shows the amount of transpiration.

This method, used in observations throughout the growing period, is quite labour-consuming. In the first place, to obtain reliable results the lysimetres have to be rather large, with an area of between 700 and 1,000 square centimetres and a depth of 80 to 100 centimetres. A lysimetre of that size containing a block of soil may weigh as much as 120 kilograms. Lysimetres used to study the transpiration of trees may weigh several tons. A truck hoist or similar machine is needed to transport such lysimetres to the weighing machines and back again.

Secondly, the block of soil must be dug out carefully to avoid disturbing the soil structure and injuring the plant roots. The lysimetres are designed with that in view, but it requires laborious work. Thirdly, soil blocks cannot be left in the ground

throughout the growing period since they are isolated from the surrounding soil and after a while will contain more or less soil moisture than the surrounding soil. The difference affects plant growth and evapotranspiration. For this reason the blocks have to be changed several times in the course of the growing period. Lastly, lysimetres have to be set up without disturbing the grass stand around them.

If the method is followed correctly it yields the most reliable data on transpiration and evaporation.

The present writer conducted transpiration studies over a number of years by the lysimetre method, and some of the findings are presented in Table 10. The

TABLE 10

TRANSPIRATION AND EVAPORATION

Crop and place of observation	Evapotranspiration	Transpiration	Evaporation	Percentage of transpiration	Transpiration coefficient
	(cubic millimetres)				
Spring wheat in Kamennaya Steppe	1,730	840	890	48	450
Irrigated wheat in lower Volga basin	3,970	2,040	1,930	51	320
Spring barley in Kursk Region	3,230	1,450	1,780	45	193

figures show that during the growing period transpiration comprises about half of evapotranspiration. The use of more advanced agricultural practices can raise the proportion to 65 per cent.

A point to bear in mind is that quite a lot of moisture is evaporated from the soil in the Soviet Union's

steppe zone in the 10 to 15 days between snowmelt and sowing. This is the period when the soil contains the most moisture and there is no plant cover. Evaporation also continues after the crop is harvested. Harrowing, stubble scuffling and other measures are taken to reduce it.

The problem of changing the structure of evapotranspiration will be considered when we discuss management of the hydrologic cycle to meet man's needs.

The world's average transpiration amounts to some 35,000 cubic kilometres a year, or about half of total evapotranspiration and nearly seven per cent of evaporation from the surface of the earth, including the seas. As we see, transpiration plays a big part in the hydrologic cycle.

We have now examined all aspects of the cycle except its economic component. All use of water resources takes place within the hydrologic cycle. Both water use and the effect of human activities on the soil cover and plant life tend in one way or another to disrupt the cycle to some extent. To increase his water resources, specifically those most valuable and yet in shortest supply, man must reshape the hydrologic cycle.

Since this great process involves all parts of the hydrosphere there is every reason to consider the hydrosphere a single whole. The idea that the hydrosphere is a unified system was first advanced by the eminent Soviet scientist V. I. Vernadsky.[20] The cycle links up water with other parts of nature—the soil, the plants, the atmosphere and the earth's crust—and thus interconnects them as well. This is tremendously important for the natural processes on earth. Furthermore, this enables man to influence the hydrologic cycle and manage it more effectively to suit his needs.

WATER EXCHANGE

Thanks to the cycle, the water of the hydrosphere is in constant motion and is continuously being used and renewed. The rates of water exchange in different parts of the hydrosphere vary. Let us see how the rate of exchange of the world ocean, for example, can be measured. The volume of the world ocean is a little more than 1,370,000,000 cubic kilometres. We know that 453,000 cubic kilometres of water evaporates annually from its surface, and a similar amount enters it in the form of precipitation and river discharge. Therefore, about 453,000 cubic kilometres of the total volume is renewed every year. At this rate it would take 3,000 years to renew the entire volume of the world ocean. Table 11 summarizes data on the

TABLE 11

RATES OF WATER EXCHANGE

Section of hydrosphere	Years needed for complete renewal*
World ocean	3,000
Groundwater, total	(5,000)
of which zones of more active exchange	(330)
Polar glaciers	8,300
Soil moisture	1.0
Rivers and lakes	10
Rivers	0.033
Vapour in the atmosphere	0.027

* In round figures; the bracketed figures are highly approximate.

rates of water exchange in various sections of the hydrosphere.

As we see, polar glaciers have the slowest water exchange. Only 2,900 cubic kilometres of their total volume of 24,000,000 cubic kilometres is annually lost and added.

Groundwater is renewed faster, but still, 5,000 years is too long a period for which to plan water use. It should also be remembered that most of the deep-lying groundwater is brine. In the groundwater zone of more active exchange, where there is more fresh water, complete renewal takes place in roughly 300 years. Inside this zone the rates of exchange differ greatly, from temporary groundwater, which is renewed annually, to artesian basins that are poorly drained by rivers and require many centuries for complete renewal.

Since at least half of the lakes are drainage lakes, we can estimate that renewal of all lake and river water requires approximately ten years. Comparing annual river discharge (38,830 cubic kilometres) with the volume of water in the river channels at any one time (1,200 cubic kilometres), we see that renewal takes place in only 0.033 of a year, that is, in an average of 11 days. It takes atmospheric water an average of ten days to renew itself. This intensive exchange is due to the ratio between the amount of moisture in the atmosphere (14,000 cubic kilometres) and the annual amount (525,000 cubic kilometres) entering it in the process of evaporation and transpiration from the entire surface of the earth.

CHAPTER THREE

The Water Balance and Water Resources

THE WORLD'S WATER BALANCE

By the term "water balance" we mean a quantitative expression of the hydrologic cycle and its components. The following equations characterize the water balance-sheet of the globe:

for the periphery of the land area that provides a discharge into the world ocean: $E_p = P_p - R_p$;

for inland "drainless" regions: $E_a = P_a$;

for the world ocean: $E_m = P_m + R_p$;

for the world as a whole: $E = E_p + E_a + E_m = P_p + P_a + P_m = P$, where E is evaporation, P precipitation, R river discharge, p the periphery of the land area, a the inland area and m the world ocean.

The first of these equations tells us that the amount of water which evaporates from the land periphery equals the precipitation minus the river discharge into the world ocean. As can be seen from the second equation, in the drainless regions the annual evaporation corresponds to the annual precipitation. The third equation shows that the world ocean loses more water through evaporation than it gains from precipitation, the difference being equal to the amount of

river discharge. Finally, from the fourth equation we learn that the evaporation from the entire surface of the globe as a whole is equal to the precipitation that falls on it.

All this is summarized in Table 12. The figures come

TABLE 12

ANNUAL WATER BALANCE OF THE WORLD

Item	Volume (cubic kilometres)	Depth (millimetres)
Periphery of land area (116,800,000 sq km)		
Precipitation	106,000	910
River discharge	41,000	350
Evaporation	65,000	560
Inland area (32,100,000 sq km)		
Precipitation	7,500	238
Evaporation	7,500	238
World ocean (361,100 sq km)		
Precipitation	411,600	1,140
Inflow of river water	41,000	111
Evaporation	452,600	1,251
World total (510,000,000 sq km)		
Precipitation	525,100	1,030
Evaporation	525,100	1,030

from the following sources: precipitation from a chart drawn up by the Central Geophysical Observatory and published in the Climate Atlas (1960), as well as from later data for the separate regions; river discharge from the map of the world's streamflow compiled by the present writer (Fig. 3); evaporation in different parts of the globe was calculated on the basis of the equations listed above.

The world's total annual precipitation exceeds half

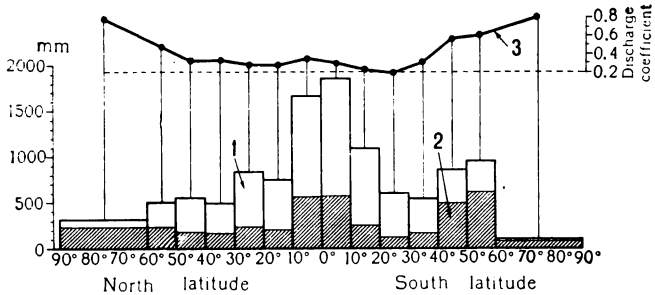


Fig. 4. Distribution of precipitation (*1*), river discharge (*2*) and discharge coefficients (*3*) by latitudes

a million cubic kilometres, which equals a depth of 1,030 millimetres. The same amount of water evaporates, 86 per cent of it from the world ocean and 14 per cent from the land area. River discharge into the world ocean, including the ice discharge of polar glaciers, amounts to 41,000 cubic kilometres a year, or 36 per cent of the precipitation falling on the periphery of the land area. The ratio of river discharge to precipitation is called the discharge coefficient, which shows the share of precipitation in the discharge and is expressed either in percentage or as a fraction (0.36 in the given case). Inland river discharge amounts to only 730 cubic kilometres a year, and the corresponding coefficient is 0.11. Global river discharge equals 41,730 cubic kilometres. Dividing this by the 113,500 cubic kilometres of precipitation falling on the land area, we get a coefficient of discharge equal to 0.37.

The rivers of the periphery of the land area discharge 1,300,000 cubic metres of water into the world ocean per second and 112 cubic kilometres daily. The

fluctuations of these amounts are insignificant, inasmuch as a seasonal or yearly abundance of river water in one area of the world compensates for a decrease in volume in another area.

Fig. 4 shows the precipitation, river discharge and coefficients of discharge in the various latitudes of the land area.

Neither the water balance equations cited at the beginning of this chapter nor the world's water balance calculated by using these equations can satisfy us completely, since they do not reflect the groundwater or soil factors. We have worked out a method of assessing these factors, which is set forth below.

WATER BALANCE OF THE LAND AREA

Streamflow has two constituents—surface runoff and groundwater—which differ both in origin and properties. From the viewpoint of the world ocean's water balance it does not matter if these two are combined, but when we study the water balance-sheet of parts of a continent, say, of a large river basin, their separate assessment acquires practical importance.

The inland hydrologic cycle (Fig. 5) is expressed by the following system of equations of the balance:[21]

$$P=S+U+E;\ W=P-S=U+E;\ R=S+U;\ E=N+T;$$

$$K_u=\frac{U}{W};\quad K_E=\frac{E}{W}=1-K_u$$

where P is precipitation; R, river flow; S, surface (flood) runoff; U, groundwater (permanent) discharge into rivers; E, evapotranspiration, which is the sum of N (soil evaporation) and T (transpiration); W, overall soil moistening, or the amount of rain and snow water that infiltrates the soil; K_u and K_E are, respectively, the coefficient of groundwater discharge into

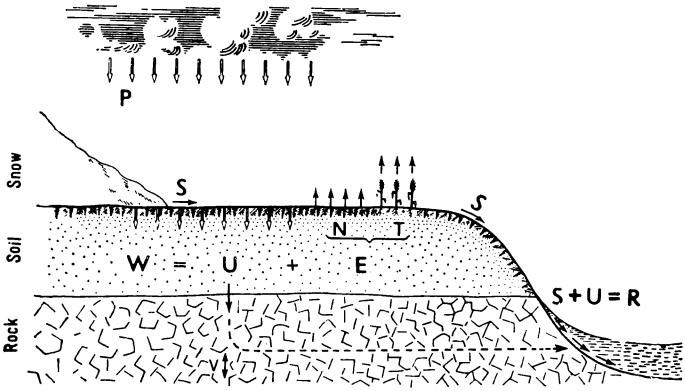


Fig. 5. Water balance of a river basin:
R—total river flow; P—precipitation; S—surface (flood) runoff; U—groundwater (permanent) discharge into rivers; W—overall soil moistening; N—soil evaporation; T—transpiration; E—evapotranspiration; V—exchange with groundwater lying below river drainage level

rivers and the coefficient of evaporation, showing what portion of the total water that moistens the soil (W) becomes groundwater which discharges into rivers, and what portion evaporates.

Estimating the lithogenous constituent of the water balance of river basins is a fairly complicated and painstaking job. In periods with little rainfall, and also in winter, when precipitation is in the form of snow and floodwater does not form, rivers are fed exclusively by groundwater. This served as a basis for calculating the share of groundwater in streamflow.

By comparing daily river flow with daily precipitation and air temperature (Fig. 6) we can establish periods during which the surface or flood runoff is

practically absent (July and August) and periods when it is combined with groundwater flow (January to July and September to December).

Thanks to this method, which was developed at the Institute of Geography of the USSR Academy of Sciences, hydrologists were able, for the first time, to determine the overall renewable reserves of groundwater.

Unfortunately the method allows us to estimate only the part of the renewable reserves of groundwater that is drained by rivers. It does not reveal the amount of water below the drainage level, that is, which does not feed rivers. As we have noted, however, this is stagnant water which takes little part in the hydrologic cycle. The degree of stagnation varies, but on the whole the groundwater that feeds rivers evidently moves several hundred times faster than the water which lies below the river drainage level. Nor does this method take into account the discharge

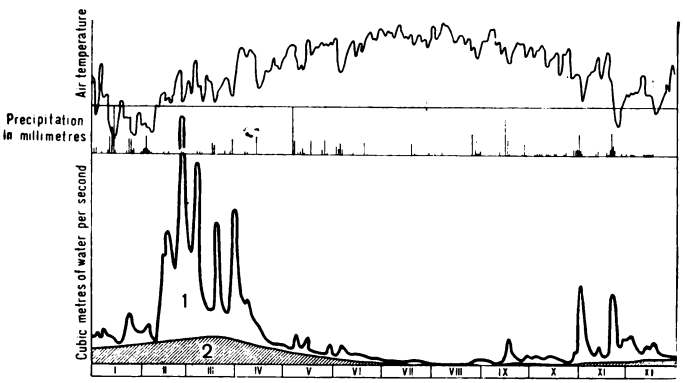


Fig. 6. Combined chart of water discharge, air temperature and daily precipitation
1—surface runoff; *2*—groundwater flow

of groundwater directly into seas, bypassing streams. In the chapter dealing with the hydrologic cycle we noted that such submarine discharge was evidently insignificant compared with the amount of groundwater that reaches the seas after it has been drained by, and become part of, rivers. Nevertheless, the time has come to make a study of this process, a knowledge of which is essential in arriving at an accurate picture of the world's water budget.

Imperfect though it is, the integrated method of water balance study is important because it marks a major advance in our understanding of the water balance and water resources. Whereas the former method analyzed the interaction between three elements of the balance-sheet, the method proposed and applied by us establishes the interconnections between six elements, including groundwater flow, or renewable groundwater resources, which could not be assessed by the previous methods.

This method has come into fairly wide use. It was employed in compiling the first balance estimate of the water resources of the Soviet Union[2,22] and is applied in Bulgaria, Rumania and Yugoslavia. Recently, workers at the Institute of Geography of the USSR Academy of Sciences completed a vast and important study of the water balance of the regions of the world, using the integrated method. Their main findings are set forth below.

FRESH WATER RESOURCES

Streamflow, groundwater, soil moisture and other water resources used to be assessed separately, independently of one another. This approach, which is still sometimes followed today, leads to wrong conclusions and misunderstanding.

There is a direct connection between soil moisture and streamflow, as was shown above. An increase in soil moisture at the expense of the surface constituent of streamflow results in a decrease in surface runoff and in streamflow.

Steps to increase soil moisture by the retention of surface runoff are now being taken and are planned on a steadily growing scale for the future, but the planners fail to take into account the effect this will have on streamflow. In planning hydroeconomic measures, streamflow data for the past 30 to 40 years, and in some cases 60 to 80 years, are used, without allowance for the fact that part of the water that once flowed into rivers now remains on the fields and that streamflow is reduced.

Such inconsistency should not be tolerated. Planning which ignores the unity of the hydrosphere will lead to negative practical results.

Scientific advances have now brought us closer to making a reliable assessment of water resources by means of the water balance method.

The study of the world's water balance with the use of equations relating to various elements of the hydrologic cycle was first conducted seventy years ago by our countryman E. A. Brikner.[23] Since then about a dozen variants of this balance-sheet have appeared. Each has improved on the previous ones, chiefly by supplying a wider range of data on the main water balance items previously studied, that is, precipitation, river flow and evaporation. The methods used in the studies have differed, in one way or another. Thus, R. Fritsche[24] and G. Wüst[25] used river flow data generalized according to ten-degree latitudinal belts. The studies by the present writer differed from the previous ones in that they were based on the first maps of the world's river discharge.[7]

M. I. Budyko calculated evaporation from the radiation balance, and then estimated river discharge from the difference between evaporation and precipitation.[26] The same method was used by L. I. Zubenok,[27] and a similar one by F. Albrecht.[28] Mention should also be made of the world water balance estimates drawn up by R. Nace[29], the world river flow estimates made by V. D. Bykov, and other investigations.

Studies of the water balance of the continents that have been completed at the Institute of Geography of the USSR Academy of Sciences differ from all previous investigations thanks to employment of the method described earlier. This method has been used in drawing up a general estimate of the world's fresh water resources[30] and also water balance maps of each of the continents and the world as a whole.

One of the difficulties in drawing up water balance maps is that substantial land areas, particularly in Asia, Africa and South America, have been either little studied or not studied at all from the hydrological point of view. To be more exact, this refers to initial data. There was more information on streamflow, and less on its constituents.

This is a major but not insuperable difficulty. Soviet hydrology accumulated a good deal of experience in this respect in the thirties, when economic development was going ahead vigorously under the early five-year plans and could not be held up until the shortage of water data was made good by observations. It was then that methods of solving hydrological problems on the basis of interpolation were evolved. There is also a substantial amount of similar experience abroad. For example, precipitation and air temperature curves have been used to determine streamflow; however, these curves are insufficiently substantiated and are not accurate enough.

In the present study we used interpolation dependences based on the idea of water balance structural curves. These were employed by us at first to estimate changes in the water balance and streamflow of separate river basins, and afterwards to study zonal regularities of the Soviet Union's water balance, discussed in the following section. We now have at our disposal similar structural curves for Africa, South America and South Asia.

The interpolation dependences differ from structural curves in that soil moisture supply is replaced by precipitation. In some cases, streamflow was also determined in relation to precipitation. The zonal principle, however, is followed in the interpolation curves as well. All these dependences contributed to an approximate assessment of the water balance within the corresponding geographical zones.

For mountainous areas, water balance elements are interpolated in relation to elevation above sea level. This is justified, for the regularities of altitude belts in mountains are analogous to the regularities of geographical zones.

Curves of this kind have been drawn for the Caucasian, Central Asian, Altai and other mountainous areas of the Soviet Union, as well as for the Southern Carpathians and the Balkans. A similar investigation was conducted for the Alps in connection with the mapping of Europe's water balance.

Interpolation is a valuable tool in obtaining an approximate idea of the water resources of countries that have not been studied from the hydrological point of view. This particularly applies to developing countries. We do not share the view of hydrologists who maintain that conclusions can only be based on observations made by a network of stations. Soviet experience shows that the method of analogy, based

on interpolation, can help to solve many problems even if initial data are scarce or non-existent.

Gauging stations still have to be set up on at least forty per cent of the earth's land area, but until they are, approximate conclusions can be made. Science can do much to fill in the gaps in observation data.

In cases where a region or country has been extensively studied from the hydrological point of view, mapping is helpful as a method of summing up the elements of the water balance.

With the decades of accumulated experience, hydrological mapping can now be carried out on a scientific basis. Correct choice of the scale of a map, depending on the amount of initial data and the distribution of the elements of the water regimen, is important. In generalized maps, such as the map of the flow of the world's rivers (Fig. 3), smooth water balance variation curves are permissible. As far as local large-scale maps are concerned, smooth curves are not always justified since the boundaries between a forest and a field, or between ploughland and urban territory, often may be associated with a sharp change in the formative factors of the water balance items.

Our aim was to compile generalized maps of the water balance of the continents. Detailed maps cannot be made at this juncture because the required hydrological data are not yet available for large parts of the world. It would hardly do to depict one region in greater detail (Europe, for example) and other continents, such as South America, Africa and Asia, more schematically. Therefore, we generalize the maps more or less uniformly for all parts of the world. The only difference is that the water balance items of the better-studied countries are more precise.

The most reliable figures in Table 13 are those for river flow, mainly because much more data have been pub-

lished on this item of the water balance than on the daily discharges needed in order to estimate groundwater discharge and surface runoff. Furthermore, detailed streamflow maps, based on all available national data, have been compiled in a number of countries. For instance, data from nearly 6,000 sites was used in plotting the streamflow map of the Soviet Union.[22]

Similarly, detailed maps have been drawn up in other socialist countries of Europe, in some West European countries, the United States, Venezuela (the River Plate basin), Australia and other countries and regions.

There are several other additional factors that make for greater reliability of the streamflow figures. First, territorial coverage is much more representative in the case of streamflow observations than for precipitation, since the former relate to more or less large drainage basins while the latter are associated with points. This is particularly important in areas with a broken relief, where precipitation varies considerably depending on elevation and slope exposure. Second, in the case of regions with unstudied streamflow, interpolation of the latter is more reliable than interpolation of groundwater discharge and surface runoff. Third, the accuracy of the latter two items is reduced by the approximate nature of the classification. Least accurate of all are the data on evaporation and overall soil moistening because of the possible summation of errors made in assessing precipitation and streamflow, in the case of evaporation, and errors in precipitation and surface runoff values, in the case of soil moistening.

The summarized data of Table 13 are relatively reliable. In terms of unit area (in depth of streamflow, mm) South America is richer in water resources than any other region. It has nearly twice as much stream-

TABLE 13

WATER BALANCE AND FRESH WATER RESOURCES OF THE WORLD'S REGIONS, THE SOVIET UNION AND ALL LAND AREAS[13, 31-33]

Items	Europe*	Asia	Africa	North America**	South America	Australia***	All land areas****	Soviet Union
Area, mln sq km	9.8	45.0	30.3	20.7	17.8	8.7	132.3	22.4
				In mm				
Precipitation, *P*	734	726	686	670	1,648	736	834	500
River discharge: total, *R*	319	293	139	287	583	226	294	198
River discharge: of underground origin, *U*	109	76	48	84	210	54	90	46
River discharge: of surface origin, *S*	210	217	91	203	373	172	204	152
Overall soil moistening, *W*	524	509	595	467	1,275	564	630	348
Evaporation, *E*	415	433	547	383	1,065	510	540	300
				In km^3				
Precipitation, *P*	7,165	32,690	20,780	13,910	29,355	6,405	110,305	10,960

River discharge	total, R	3,110	13,190	4,225	5,960	10,380	1,965	38,830	4,350[5]
	of underground origin, U	1,065	3,410	1,465	1,740	3,740	465	11,885	1,020
	of surface origin, S	2,045	9,780	2,760	4,220	6,640	1,500	27,545	3,330
Overall soil moistening, W		5,120	22,910	18,020	9,690	22,715	4,905	83,360	7,630
Evaporation, E		4,055	19,500	16,555	7,950	18,975	4,440	71,465	6,610
		Relative values							
Percentage of groundwater in river flow		34	26	35	32	36	24	31	25
Coefficient of groundwater discharge into rivers		0.21	0.15	0.08	0.18	0.16	0.10	0.14	0.13
Coefficient of streamflow		0.43	0.40	0.23	0.31	0.35	0.31	0.36	0.40

* Including Iceland.
** Excluding the Canadian Archipelago and including Central America.
*** Including Tasmania, New Guinea and New Zealand. On the continent proper: $P = 440$ mm, $R = 47$ mm, $U = 7$ mm, $S = 40$ mm, $W = 400$ mm, $E = 393$ mm.
**** Excluding Antarctica, Greenland and the Canadian Archipelago.
[5] Not counting 300 sq km of transit flow.

flow and groundwater discharge into rivers as Europe, which ranks second in water resources. Next come Asia, North America and Africa and last of all Australia.

In terms of volume of streamflow and groundwater flow, which depends on the size of area, Asia ranks first, followed by South America, North America, Africa, Europe and Australia.

To get a full picture of the world's fresh water resources we must add to the total figures of Table 13 the water and ice flow from the polar glaciers of Greenland, the Canadian Archipelago and Antarctica. Nearly the entire surface of those land areas is covered with glaciers, from which there is a flow into the world ocean in the form of icebergs, in the form of water resulting from the ablation of glaciers during the short summer, and in the form of snow blown off the Antarctic ice sheet.

We have estimated the annual flow from Greenland and the Canadian Archipelago at approximately 700 cubic kilometres, or 180 millimetres in depth, and the flow from Antarctica at 2,200 cubic kilometres, or 150 millimetres in depth. The basic elements of the water balance of the world's land areas, with these figures included, are shown in Table 14.

TABLE 14

BASIC ELEMENTS OF THE WATER BALANCE OF THE LAND AREAS OF THE WORLD, INCLUDING FLOW FROM THE POLAR GLACIERS

	Precipitation, P	Flow, R	Evaporation, E	Coefficient of flow, K_R
km^3	113,500	41,730	71,770	
mm	760	280	480	0.37

The stable water resources of streams do not come from groundwater alone. Streamflow regulated by lakes under natural conditions, as well as by man-made reservoirs, also comes into the picture.

Flood streamflow, that is, streamflow minus total stable flow, should be regarded largely as potential water resources. This type of discharge, which causes no little damage to man, is a big reserve for the extended reproduction of water resources.

Aggregate flow of all the rivers of the world, not counting the polar glaciers, is 38,830 cubic kilometres; together with the flow from Greenland (plus the Canadian Archipelago) and Antarctica, it equals 41,730 cubic kilometres, with corresponding streamflow depths of 294 and 280 millimetres. About 730 cubic kilometres of this amount is accounted for by inland ("drainless") regions. All the rest of the river and glacier flow, amounting to 41,000 cubic kilometres, discharges into the world ocean, forming on its area a layer 111 millimetres deep.

On the basis of the maps a balance-sheet of the water resources of the countries of the world has been drawn up. As far as we know, this is the first-ever assessment of the water resources for approximately half of the countries. For example, only 14 of the 50 African countries have hydrological data for a study of the water balance. The work that has been done is very important for the developing countries. It is also important for the industrial countries of Europe and North America, for which the water balance, including groundwater discharge into rivers, surface runoff and soil moisture resources, has been compiled for the first time.

The data of Tables 13 and 14 as well as the methods of obtaining them constitute another step forward in man's knowledge of the water balance and water

resources of the world. Looking back, one cannot help noting the substantial advances made in the past few decades. This progress is associated, in part, with an increase in the volume of hydrometeorological information. However, the increase in the information necessary for drawing up the world's water balance is not keeping in step with the advances in the theoretical understanding of this problem and in methods of tackling it.

TABLE 15

PER CAPITA WATER RESOURCES

	Population in millions (1969)	Annual streamflow, km³		Streamflow per capita, cubic metres a year	
		total	aggregate stable	total	aggregate stable
Europe	642	3,100	1,325	4,850	2,100
Asia	2,040	13,190	4,005	6,465	1,960
Africa	345	4,225	1,905	12,250	5,500
North America	312	5,960	2,380	19,100	7,640
South America	185	10,380	3,900	56,100	21,100
Australia *	18	1,965	495	109,000	27,500
Total	3,542	38,830	14,010	10,963	3,955

* Including Tasmania, New Guinea and New Zealand.

To get an idea of how well the people of the world are supplied with water, we must examine the per capita fresh water resources, specifically streamflow. These data are given in Table 15.

Aggregate stable streamflow in Table 15 means streamflow of groundwater origin plus the flow re-

gulated by lakes and reservoirs. These are the fresh water resources most available for use. The figures in the next to the last column include flood water, which is a significant potential source of fresh water.

We see from these figures that Europe and Asia are the most poorly supplied regions, while South America and Australia are the best supplied. In the latter case, this is connected with the fact that New Guinea and New Zealand have very large rivers and a relatively small population. If we take the Australian continent proper, total streamflow resources per capita drop to 24,000 cubic metres a year and stable streamflow to 3,500 cubic metres, that is, to 20 per cent and 13 per cent, respectively, of the figures in the table. Nevertheless, the Australians have more fresh water resources per person than the inhabitants of Europe and Asia. The population of South America is the best supplied of all.

The reader should bear in mind that the above figures on the amount of fresh water available per inhabitant of the various regions are highly generalized.

In the first place, per capita needs vary greatly depending on the level of industrial development and of irrigation farming, which consumes a large amount of water. The modern city dweller, who has centralized water supply and sewage systems, uses much more water than the rural inhabitant. In the second place, water resources and population are unevenly distributed on the continents. For example, most of the vast drainage basin of the Amazon, the world's largest river, is very sparsely inhabited. On the other hand, quite a few densely populated industrial countries and regions have small resources of fresh water. This problem has to be solved within the boundaries of the respective countries and regions, with a whole

series of factors taken into account. We shall look into some of these below.

Despite its shortcomings, an assessment of the per capita resources by continents has meaning in view of the future possibilities of transferring water from abundantly supplied areas to areas having meagre resources. Water diversion projects on a fairly large scale are now being drawn up in the Soviet Union and North America. In future, the growing need for extensive transfer of water will undoubtedly go hand in hand with new economic and technical possibilities for carrying out such projects on the scale of entire continents.

The figures of Table 15 are also interesting from the point of view of the potentialities of extended reproduction of fresh water resources, that is, of utilizing flood flow to increase the aggregate stable streamflow. We shall deal with this problem in greater detail in our discussion of ways and means of improving water resources.

ZONAL PATTERNS

When we describe the hydrologic cycle of the globe or of extensive land areas, we do so in generalized terms. Actually, the water balance structure depends on geographical features and is, as we have noted, the result of the interaction of water with climate, soil, vegetation and terrain. The sum-total of these factors determines a region's chief geographical features, which, as we know, vary from zone to zone.

Table 16 gives a zonal picture of the Soviet Union's water balances.

Overall soil moistening is greatest in the Ussuri taiga on the Pacific seaboard, in the mixed forest subzone and in the forest-steppe zone. North of these zones the amount drops because the soil cannot ab-

TABLE 16

ZONAL TYPES OF WATER BALANCE IN THE SOVIET UNION

	Characteristic quantities				
	Overall soil moistening, W (mm)	Groundwater discharge into rivers, U (mm)	Evaporation, E (mm)	Coefficient of ground water discharge into rivers, K_u	Evaporability, E_{max} (mm)
Tundra (including forest-tundra)					
European	300	90	210	0.30	250
Siberian	300	115	185	0.38	290
Taiga					
European	350	70	280	0.20	450
West Siberian (central taiga, plains)	350	70	280	0.20	370
East Siberian (mountainous)	280	80	200	0.29	370
Permafrost zone	250	25	225	0.10	340
Amur area	320	30	290	0.11	450
Ussuri area	550	60	490	0.11	700
Forest mixed					
European	420	55	365	0.13	500
West Siberian (southern taiga)	350	40	310	0.11	400
Forest-steppe					
European	400	15	385	0.04	600
West Siberian	380	15	365	0.04	500
East Siberian	300	10	290	0.03	450
Steppe					
European	300	3	297	0.01	750
West Siberian and North Kazakhstan	280	2	278	0.01	650
Semi-desert	200	1	199	0.005	1,000

sorb the precipitation before a significant share of it is lost in surface runoff. To the south, the amount drops because there is less precipitation. Groundwater discharge into rivers is greatest in the tundra and taiga zones, except for regions where permafrost prevents water from penetrating deep below the surface and forming groundwater. In the steppe zone a large part of the soil moisture is lost in evaporation, and very little of it remains to form groundwater.

The coefficient of groundwater discharge into rivers (K_u) is greatest in the tundra (0.30 to 0.40) and is fairly high in the northern taiga (0.20 to 0.30). In the permafrost zone it is from one half to one-third as much as in northern taiga districts where there is no permafrost. In the steppe and forest-steppe zones only from one to four per cent of the soil moisture goes to feed groundwater to be ultimately discharged into rivers (K_u 0.01 to 0.04), while 96 to 99 per cent is evaporated.

Table 16 includes figures showing the maximum possible evaporation when the soil is constantly saturated with moisture. The evaporation potential depends chiefly on climatic conditions. A comparison of the water balance factors with evaporability shows the role played by a warm climate in shaping the water balance. As evaporation increases, a region's overall soil moistening and groundwater discharge into rivers decrease.

Zonal water balance patterns in the rest of the globe have not yet been analyzed in similar detail, but if we go by analogy with the territory of the Soviet Union and use data on regions of the southern hemisphere that have no geographical counterpart in the Soviet Union, we arrive at the figures given in Table 17.

The water balance structures in the main zones of the northern and southern hemispheres have features

TABLE 17

TYPES OF WATER BALANCES IN OTHER AREAS OF THE WORLD

Zone	River basin	Typical values* (mm)			
		W	U	E	K_u
Semi-desert	Zak (South Africa	185	1	184	0.005
Savanna	Shari (Equatorial Africa)	940	10	930	0.01
Subtropical evergreen forest of Mediterranean type	Dorn (South Africa)	490	5	485	0.01
Tropical forest shedding leaves in dry season	Murakshi (Equatorial Africa)	1,060	110	950	0.10
Moist evergreen tropical forest	Nanmitsian (Chinese People's Republic)	1,100	250	850	0.18

* Designations the same as in Table 16.

in common. For example, the semi-deserts of the Soviet Union and South Africa, or the forest-steppe zone and African savanna. The savanna gets more precipitation but it has greater evaporation, so that the K_u values are very close.

The differences in water balances reflect differences in the nature of the hydrologic cycle in the corresponding zones. In zones of excessive soil moistening the lithogenous arc plays a relatively larger part in the cycle, while the surface section is relatively less

dynamic. That is because the soil is saturated and the climate is cool.

The surface arc is the most dynamic part of the water cycle in the arid zones—the steppes and the semi-deserts. Here the cycle's lithogenous arc is inert owing to the relatively low permeability of the soil and the fact that the bulk of the soil moisture is evaporated. The deserts are an extreme example. Here only a negligible amount of groundwater is formed and the fairly big reserves of deep-lying groundwater are stagnant. The latter were formed in previous geological periods when the soil of these regions received much more moisture. They lie too deep under the desert to evaporate and they did not drain away into other areas. Desert groundwater is recharged to some extent by surface water formed during cloudbursts or snowmelt on the *takyrs*.

In the wadi of the Sahara, the omurambo of the Kalahari and the intermittent rivers of other deserts, underflows of water through alluvial deposits are often observed.

LOCAL FEATURES

Physico-geographical conditions usually vary a good deal within zones, and this affects local water balance structure. Sometimes adjacent tracts of land have sharply differing balance structures because their soils differ widely, particularly as regards permeability. Within a zone, for example, forest soil is usually more permeable than the soil of the fields, although the climatic conditions are the same. The hydrological properties of field soils also differ greatly, depending particularly on the use to which the fields are put (pasture, hayland or ploughland) and the way in which the ploughland is cultivated. The same is true of for-

ests. A productive forest regulates its water supply better than one that is not very productive. The water balance and plant productivity are closely interconnected.

Soil and vegetation are the main factors that shape the intrazonal features of the water balance. Consequently, it is essential to take soil hydrology into account when studying the intrazonal and economic features of the water balance. Intrazonal water balance differences often overshadow differences between geographical zones.

This is illustrated by data on spring surface runoff in various parts of a district with uniform climatic conditions in the mixed forest zone of the European part of the Soviet Union, presented in the section dealing with the participation of the soil in the hydrologic cycle.

The type of land and type of soil determine the soil's hydrophysical properties. Ploughland absorbs more water than meadowland. Forest soil has an excellent permeability. On sandy loam the runoff coefficient on meadows and fallow land is 11 times greater than in the forest, and on sandy soil it is 20 times greater.

Other examples that were presented above illustrate the great diversity of water balance formative factors within each zone. Each ecosystem, right down to elementary landscape units, has its own specific features in this respect. Intrazonal water balance diversity is determined chiefly by the soil. The vegetative cover is also an important factor in the intrazonal water balance. In part, it has independent significance (the role of transpiration, the influence on albedo and other elements of the radiation and heat balance), but its main influence on the water balance is exercised thro-

ugh the soil inasmuch as vegetation is one of the chief factors in soil formation.

The diversity in local features of the water balance is due not only to natural factors, chiefly soil and vegetation, but also, and sometimes in still greater measure, to man's influence on the soil. For example, in the steppe and forest-steppe zones spring surface runoff from a field ploughed in autumn is one half to one quarter as much as from a similar field ploughed in the spring or sown to a winter crop. That is because much more water infiltrates topsoil made friable by autumn ploughing than it does soil under stubble after spring ploughing or on a winter-field. Autumn ploughing thus helps to increase soil moisture reserves.

Man is able to regulate the local water balance because it depends to a great extent on the properties and condition of the soil. Since the water balances of large territories reflect those of separate areas, man is capable of regulating the former too, including the water balances of large river basins, by acting on the topsoil and vegetation. Below, we shall see how improved cultivation of the soil in the Don River basin, where ploughland occupies nearly three-quarters of the area, has substantially influenced the water balance and streamflow as a whole.

While our present knowledge of the intrazonal factors that influence the water balance is undoubtedly an appreciable step forward, a great deal still has to be done. Actually, this is a problem which hydrology has only just begun to study. It is complicated by the fact that it largely depends on the establishment of a network of water balance stations that make an experimental study of the mosaic-like distribution of the local, intrazonal, water balance, of its structure and main features, and also of the natural factors and

man's influence. Sizeable river basins, including representative ones, cannot make any appreciable contribution to these studies because they usually encompass diverse intrazonal factors affecting the water balance and streamflow.

It is necessary to break up a region into elementary ecosystems, each of which has a specific water balance. The selection of typical key sections of this kind and conducting on them of a suitable complex of hydrometeorological, soil and geobotanical (or agronomical, in the case of ploughland) investigations carried out according to unified methods, including the comparative method, will provide the basic material for compiling large-scale hydrological maps.

We should not close our eyes to the fact that water balance stations, whose development has been going on since the thirties, particularly in the United States, have failed to live up to the expectations as regards the study of the intrazonal aspects. The stations were well equipped but their theoretical foundations were far below the mark, and therefore the present writer's attempts to sum up the extensive results of these observations did not yield the desired effect.

The same can be said of some of the water balance stations set up in the Soviet Union, although many of them have provided material for valuable generalizations and conclusions, some of which are presented in this book, in the chapter "Controlling the Hydrologic Cycle". Comparison of similar intrazonal features in different geographical zones on the basis of observations at water balance experimental stations were particularly fruitful (see Fig. 7 on page 172).

In recent years hydrologists have attained a fairly high degree of proficiency in solving problems on a zonal scale, but so far only the first, although substantial, steps have been made in studying intrazonal

patterns. The further development of hydrology, as we see it, should be focused on the study of intrazonal regularities as elementary units of hydrological mesosystems and macrosystems.

TODAY'S WATER RESOURCES

Now that we have considered the main aspects of the hydrosphere, the hydrologic cycle and the water balance, we can go on to an assessment of today's water resources. But first let us agree on what should be regarded as water resources.

Broadly speaking, we look on all the free water in the hydrosphere as water resources. This excludes the chemically and physically bound water that is part of minerals and living organisms.

Water resources include the rivers, lakes, canals, reservoirs, swamps, groundwater, soil moisture, mountain and polar glaciers, the seas and oceans, and atmospheric water.

The use of water resources differs from the way in which other natural resources are used. For example, after coal and oil are extracted and burned, or are used as raw materials in the chemical industry, they cease to be coal and oil, turning into carbon monoxide and many other substances. But no matter how water is used it remains water; sometimes it merely changes its state, turning into vapour or becomes polluted. Irrespective of the use to which it is put water continues to be part of the hydrologic cycle.

The only exception is a small amount of water that in the process of production becomes chemically bound as part of the finished product.

It follows that water resources can be divided into two distinct groups: the *stationary reserves*, described in the first chapter (Table 1 on p. 18), and the *renew-*

able reserves that make up the dynamic part of the hydrologic cycle and are estimated by the balance method (Table 13 on p. 84). Thanks to the hydrologic cycle, all constituents of the hydrosphere, including deep underground water, are renewed at varying rates. Hence, if man does not use more water than the volume that is renewed by the hydrologic cycle, the reserves will be *inexhaustible and permanent.*

However, he sometimes does use more. During the past few decades the water table in many artesian basins has been dropping steadily because more groundwater has been used than is renewed. If this continues, the basins will be depleted and cease to exist as a water source.

As we shall see, steps can be taken to put an end to this process and even to increase the renewable resources of groundwater. But such steps have to be planned, and to do that we must know the rate at which the reserves are renewed. The water exchange rates in different parts of the hydrosphere are shown in Table 11 on page 70. When planning the use of water from a specific source, however, we must know its balance sheet.

An analogous situation exists in many of the world's groundwater systems. In maritime areas the water renewal process is accompanied by the flow of sea water into aquifers in place of depleted fresh water. This has been observed, for instance, on the coast of the North Sea and on Long Island in New York.

Besides planning the exploitation of water resources within the limits of their renewable reserves it is permissible in some cases to plan water use in amounts exceeding those reserves, that is, at the expense of stationary reserves. This can be done where the stationary volume is far greater than the amount being used and where exploitation of stationary reserves

does not affect the state of other components of the hydrosphere, that is, other sources of water.

Deep-lying groundwater is an example. There is a vast amount of this water (Table 1 on p. 18), and where it has to be used it will last for a long time. It is important to consider, though, whether its use would affect the state of the groundwater in the active exchange zone or the natural drainage of groundwater by streams. A clear answer to this question requires a programme of complicated research. Another point to bear in mind is that deep-lying groundwater is often saline, and sometimes concentrated brine. This greatly restricts its use.

Polar glaciers are an example of the possibility of exploiting slowly renewed reserves of water. Their volume amounts to almost 24,000,000 cubic kilometres. If this source has to be used in future it will last a long time. If 25,000 to 30,000 cubic kilometres of water a year were to be drawn from the polar glaciers, that is, ten times as much as the volume of their annual renewal, they could serve as a source of supply for 1,000 years.

The above examples sound like science fiction today, but man may find in future that he has to draw on these sources of water too.

Another important division of water resources is into *fresh* and *salt water*. Salt water can obviously be used to a very limited extent, and desalination is expensive. For most practical purposes we need fresh water, a circumstance that sharply reduces the resources that can be used. Out of the 1,455 million cubic kilometres of water that make up the hydrosphere 1,427 million cubic kilometres, or more than 98 per cent, is salt water that is mineralized to varying degrees. The water that takes a direct part in the hydrologic cycle (the reserves which are renewed annually)

is, because of its mobility and frequent change from vapour to water to ice and back again, mineralized to a slight degree and is usually *fresh* water.

Stability in time is another important factor that has to be taken into account when assessing water resources. We have mentioned that the regimen of rivers fluctuates from season to season and from year to year. The most valuable water resources are those which are reliable, since for almost all practical purposes it is important *always* to have a definite amount at one's disposal.

Table 18 shows how resources can be classified according to the quality of the water and the degree to which it is dependable and capable of being regulated.

TABLE 18

WATER RESOURCES GRADED ACCORDING TO SUITABILITY FOR USE

Quality of water / Degree of regulation	High (A)	Medium (B)	Low (C)
High (I)	I A	I B	I C
Medium (II)	II A	II B	II C
Low (III)	III A	III B	III C

Consumers' requirements vary, of course. For example, drinking water has to meet the highest standards and its sources must be well regulated, in other words it has to be Grade I A. I A, II A and even III A water may be used for irrigation if the supply is sufficient during the period of plant growth. In hydropower generation the degree to which the supply can be regulated is more important than the quality of the

water. And so on and so forth. Water resources can be raised from Grade III A to II A or I A by means of reservoirs or land improvement measures. Desalination can turn low-grade I C water into I A water. The transfer of water resources from inaccessible lower classes to higher classes of resources that are more suitable and convenient for use is a form of their *extended reproduction.*

This system of classification is not yet being applied. Our suggestion poses a problem which, with the increasing use of water resources, has become urgent.

The figures presented in Table 13 do not give a complete picture of the reserves of the most important water source, namely, reliable streamflow. Stable runoff of groundwater origin amounts to 11,850 cubic kilometres a year in the world as a whole and 1,020 cubic kilometres a year in the Soviet Union. But there is also lake-fed stable streamflow, for example, the discharge of the St. Lawrence River in North America, regulated by the Great Lakes system, that of the Angara river in Siberia, regulated by Lake Baikal, and that of the Neva river in the European part of the Soviet Union, regulated by a vast system of lakes, including Lake Ladoga, Europe's largest. Counting lake-regulated discharge, the world's total stable streamflow amounts to about 12,200 cubic kilometres and the Soviet Union's to 1,120 cubic kilometres. To this should be added the river flow regulated by reservoirs, whose total regulating possibilities on all the rivers of the globe exceeds 1,840 cubic kilometres, including more than 300 cubic kilometres in the Soviet Union. These figures show that significant steps have been taken to increase stable runoff resources, the most valuable from the economic point of view, which exceed 14,000 cubic kilometres a year.

There are good prospects for such management of water resources in future.

Counting the flow regulated by lakes and reservoirs, and excluding the discharge from polar glaciers, the world's flood flow now amounts to approximately 24,800 cubic kilometres a year, and not 27,545. The corresponding figures for the Soviet Union are 3,050 and 3,330 cubic kilometres. In these calculations we allow for the fact that the drop in flood flow thanks to the regulating action of reservoirs does not fully correspond to their available storage. This is because in some years the volume of flood flow is less than the available storage of reservoirs. We take the volume of flow regulated by reservoirs to be about 40 per cent of their available storage. It will be of primary importance in future to make fuller use of reservoirs to regulate flood flow. This has already become a matter of urgency in a number of developed areas.

To sum up, reliable streamflow, amounting to 14,000 cubic kilometres a year, 36 per cent of the total discharge of the world's rivers, is man's golden treasury. The stable streamflow in the Soviet Union amounts to about 1,400 cubic kilometres, or 31 per cent of the total river discharge. This, we repeat, is man's most valuable source of water since it provides him with a constant high-grade supply.

The stable runoff used for public water supply and irrigation is usually diverted from streams, lakes or reservoirs. But almost the same amount of water can be extracted from the ground, that is, from aquifers, before it reaches streams. This water supply method is often more costly but it has the advantage of providing higher quality, unpolluted water.

Surface (flood) runoff is a less important water source since it can be used only after changes that we shall describe later. It is a potential source for an increase

in reliable streamflow and soil moisture. This does not include the above-mentioned use of the flood run-off of mountain streams for irrigation without any preliminary regulation.

Previously, as a result of a mistaken understanding of water resources and an imperfect method of assessment, soil moisture was not included among them. The balance method has enabled it to be estimated approximately. This is important not only for agriculture, as the chief consumer of soil moisture, but also for a correct assessment of other water resources that depend on the expenditure of soil moisture.

Now a few words about precipitation, a key part of the hydrologic cycle. Actually, river flow, groundwater and soil moisture depend on precipitation, and so it is important to know precipitation when compiling an integrated balance estimate. Precipitation should be regarded as a potential water resource. In a number of places where there is no other source it is collected for water supply. Ways will undoubtedly be found in future to increase precipitation by condensing atmospheric moisture.

Evaporation from the land area cannot be considered a water source, yet it should not be regarded as a waste of water, as it often is in engineering hydrology.

It is quite obvious that evaporation from the surface of lakes should be regarded as a loss of water. Reservoir evaporation losses are especially perceptible inasmuch as they have a detrimental influence on the water balance. Soil evaporation is a negative factor in districts suffering from moisture deficiency, where this process is connected with the loss of soil moisture, an important element of fertility. However, evaporation from waterlogged land should evidently be regarded as a useful process which contributes to some

degree to natural improvement of the land. Transpiration, of course, is very useful.

In view of the aforesaid, evaporation cannot be unconditionally regarded as a negative feature of the water balance. A one-sided appraisal is sometimes made when evaporation is considered only from the standpoint of streamflow, which naturally diminishes if evaporation increases. And so, evaporation has both positive and negative features. The same can be said, in one degree or another, about nearly every other water balance item. For instance, streamflow, especially stable, regulated discharge, is the economy's most valuable source of water. However, high water, which causes floods and threatens life and property, cannot be regarded as positive. Similarly, in zones with insufficient soil moistening, surface runoff from farm fields is a very negative factor.

A major feature of water resources is that they are *highly dynamic and interconnected in the hydrologic cycle.* Because they are so dynamic they are difficult to utilize. Water has to be trapped, its flow regulated, evaporation from farm fields prevented, etc. On the other hand, it is a good thing that water resources are dynamic. For one thing, this leads to their continuous renewal. For another, thanks to this—and given certain conditions that are as yet far from always observed—*water is a permanent, inexhaustible natural resource.* Further, the interconnection between different water sources and between water and soil, rocks, vegetation and atmosphere *enables man to regulate the hydrologic cycle to meet his needs more effectively.*

Does man have sufficient water resources? There is no simple answer to this question. It all depends on his attitude to water resources, on the way he uses them. If he uses them intelligently and correctly and follows certain rules he will have enough water for-

ever. But if he uses the resources irrationally, as is now being done to a considerable degree, they will prove insufficient. Below, we shall explain what we mean by intelligent, rational use of water resources.

The water resources of the Soviet Union can be judged from Table 13 (p. 84) by comparing the constituents of the Soviet Union's water balance expressed in millimetres of depth, with those of the world's land area as a whole. The figures show water resources per unit of territory, with one millimetre of depth corresponding to 1,000 cubic metres per square kilometre.

Water requirements are perhaps the main criterion. Since water is in short supply in a number of the world's developed regions, greater attention must be paid to its proper use and conservation.

Reliable assessment of water resources is of paramount importance as the first step towards efficient utilization of water resources.

Further on in this book, when we examine the main forms of water use, the reader will gain a clearer picture of the apparently contradictory water prospects. On the one hand, as we say, the earth has rich resources of fresh water and thus can meet the needs of man forever. On the other hand, more and more is being written about the danger of water resources becoming depleted, thereby restricting mankind's development.

Proponents of the latter view point to the critical, or near-critical, state of water resources in a number of places in the world. If, say some authors, the situation in certain places is dangerous today, what will it be like in the year 2000, when the population will have nearly doubled and economic development will be incomparably greater? Their answers are highly

pessimistic.* We do not share the pessimism. We believe there are sufficient grounds for looking to the future with optimism. But this will require vigorous steps to change the principles of water use and conservation.

---

* We may refer, for instance, to the interesting but somewhat pessimistic book by R. Furon.

CHAPTER FOUR

Man's Impact on the Hydrologic Cycle

HOW WATER RESOURCES ARE USED

So far we have discussed water use in general terms. Now let us take a look at the principal ways of using and conserving water resources. This will clarify the lines along which water use will have to be improved in order to prevent a water crisis.

Man's use of water resources is closely and constantly linked up with the operation of nature's great hydrologic cycle. Regardless of how it is used, water is not removed from the cycle in the process of use but continues to take part in it. In ways that differ according to the purpose of the water and the technology by which he uses it, man transfers water from one arc or chord of the cycle to another.

Moreover, as a rule the transfer does not follow the natural course of the cycle. For example, water which we take from a river to irrigate a farm field goes largely into evaporation and transpiration. In terms of the hydrologic cycle, in this case we have transferred water from the river to the soil and then to the atmosphere, from where part of it returns to the river.

The transfer of water from one arc of the hydrologic

cycle to another leaves its imprint on water resources, in the conservation of which man has such a big stake.

Even if we were to assume that all evapotranspiration from irrigation water condensed into rain would fall in the basin of the river from which the water was removed, the river's water resources would not be fully restored. This is because part of the rainfall would seep into the soil and some would evaporate. In the temperate zone the streamflow coefficient ranges from 0.25 to 0.40, while in the arid zone it is as low as 0.1, or even less. Streamflow is restored correspondingly, but only, we repeat, if the evaporated moisture condenses into precipitation that falls in the basin of the same river from which the water was drawn for irrigation.

However, air currents can easily transport the evaporated moisture to other river basins, the inhabitants of which are not in any need of additional water. It follows that the use of water in the economy may affect the cycle adversely, although not removing it from the cycle.

We do not want to imply that man should give up water use which affects the cycle adversely. This would be absurd. Like other natural resources, water should be used in full measure for man's personal and economic requirements. But we must bear in mind that water use almost invariably brings about large or small changes in the hydrologic cycle that are bound to affect the water resources.

Even when water is taken from a river to meet domestic and industrial needs—and some industries return from 90 to 95 per cent of the water they use to the river—the cycle is affected, often to a far greater extent than when water from rivers is transferred to the atmosphere. In many cases the water that is re-

turned by industries pollutes masses of river water exceeding it in volume many times over. Here is where the chief danger of depletion of water resources lies. We shall discuss this point in detail further on.

Significant progress has been made in water use and conservation in the five and a half decades of the Soviet system. Water management was relatively underdeveloped in pre-revolutionary Russia. Many centuries ago, the rivers cutting across Russia's vast expanses were the places where people built settlements and began to develop the productive forces. Rivers were the chief transportation routes, they were also harnessed to thousands of small flour mills. In the time of Peter I many metal manufacturing plants in the Urals derived power from water wheel installations that were fairly advanced for the period. Before the Great October Revolution of 1917, however, Russia did not have a single hydroelectric power station of any considerable size. Dobrotvorsky, Klasson, Graftio and other gifted Russian engineers designed hydropower plants for a number of rivers but they were never built.

Irrigation is an ancient way of using land and water resources. In Central Asia and Transcaucasia it goes back to the first millenium B.C., if not earlier. In ancient Egypt and Babylonia the basin system, a primitive method of irrigation using the floodwaters of the Nile, Tigris and Euphrates rivers, was practised several thousand years before our era. Most of the irrigation systems in pre-revolutionary Russia were small. Russian engineering plans for irrigation systems appeared at the beginning of the present century, but few were translated into reality.

The Soviet Union has more than trebled its irrigated area in the past half-century. All the small systems have been modernized and, as a rule, converted into

large-scale networks with up-to-date engineering structures.

Only a few large cities of Russia had municipal water supply systems before the revolution of 1917. Sewage treatment was practised in only a few cities; one of them was Moscow, where the well-known agronomist V. P. Williams used sewage to irrigate farm fields.

In the early Soviet years, while the Civil War was still going on, a State Commission for the Electrification of Russia (abbreviated in Russian as GOELRO) was set up on Lenin's instructions. This took place in March 1920. The Commission, headed by Gleb Krzhizhanovsky, a prominent power engineer, drew up the first long-range economic development plan. The programme centred around the construction of 30 electric stations, including 10 hydropower plants, and envisaged development of the key industries.

Although completed decades ago, the GOELRO programme retains its significance to this day from the methodological point of view, as you will see later.

Before the Socialist Revolution, water management in Russia, with the exception of river navigation and irrigation, lagged behind that of the Western countries. Today the Soviet Union has one of the world's leading water economies, particularly in the field of hydropower development, water supply and irrigation farming.[31]

Water use is divided into two fundamentally different groups: non-withdrawal use, as in navigation, hydropower engineering and fisheries, and withdrawal use, as in water supply and irrigation systems. The difference between the two groups was greater in the past than it is today.

On the one hand, a fairly large amount of water is lost by evaporation from the reservoirs built for

hydropower stations and river navigation. The same applies to fisheries. On the other hand, water supply and irrigation schemes return some water to the rivers.

Non-irrigation farming is a very large consumer of water. As crop production grows, so does the amount of water which enters the atmosphere through transpiration from the plants. Since this is an invisible process it is not, as a rule, included in statistics. However, science has ascertained the significance of water expenditure in crop production, has developed methods of estimating the amounts, and has shown how important it is to take this factor into account in planning water use.

Streams, lakes and reservoirs are becoming increasingly important as recreation areas and tourist attractions. The use of water resources for these purposes is growing rapidly and in future will have to be planned accordingly.

Water use and conservation are closely intermeshed. Water management as a whole can be correctly organized only if water resources are conserved *in the process of their use*, only if use and conservation are rationally integrated. When use and conservation go hand in hand there will be a minimum of restrictive regulations that come into conflict with use. Water resources, like all other natural resources, are there to be used. Water use can be combined very well with keeping the landscape beautiful, the water pure and the water source in continuous operation. This calls for regulations that are an inseparable part of the process of water use itself.

There must, of course, be some conservation standards besides those concerned strictly with water use. To begin with, children should be taught from an early age—in the family, in kindergarten and especially in

school—to love nature and to cherish nature's gifts, among them water.

Laws setting forth the principles of water use and the penalties for the violation of the principles play an important part. Legislation should not, however, be limited to restrictions. It should embrace all questions connected with the use of water resources and with their conservation, chiefly in the process of use.

LONG-RANGE FORECASTING

Before going over to a brief examination of various types of water use and an attempt to draw up a long-term prognosis in each case, we feel that it would be useful to look into some general questions of the methodology of long-range forecasting. Economic planning and coordination were first practised on a national scale in the Soviet Union and then in the other socialist countries. Today the advantages of a planned economy are generally recognized, and some capitalist countries have also introduced elements of planning, insofar as this is compatible with the capitalist economic system.

In a socialist society, annual and five-year plans acquire the force of law. This is an important motive force in economic development.

Long-range plans and forecasts can provide an idea of how suitable present-day undertakings are in the light of future conditions. Contemporary trends in water use depend on the general guidelines that are drawn up for the future. This especially applies to industries that cannot be regeared easily and quickly. Short-term expansion of these industries must therefore be based on a technical policy that takes into account the conditions which will exist in a more or less remote future. If several alternative long-range fore-

casts are drawn up, the planners can select from them the measures that best solve a given problem from the physical, historical, technical and economic points of view.

Thus, long-range forecasting of water use and conservation helps to determine development trends and to choose the most effective steps to be carried out at least three or four decades in advance.

That is the view of long-range forecasting which is presented in this book and other writings by the present author.[35-40]

This understanding of the substance and aims of long-range forecasting determines some features of the methods of compiling them. One of the most difficult problems is that of foreseeing the qualitative changes on which a future-oriented technical policy should be based. A number of long-range forecasts, including a well-known American one,[1] are founded on simple extrapolation of quantitative growth of water use in accordance with the traditions and experience that exist at the time the prognosis is drawn up. In these forecasts the principles of water use and conservation, as well as consumption quotas, remain unchanged.

It is obvious that prognoses of this type, which do not take future scientific and technological progress into account, are the easiest of all to compile, but they cannot give a valid picture of development trends in the use and conservation of water resources, or indicate tasks and aims.

Let us assume, for a moment, that the GOELRO Plan, the State Plan for the Electrification of Russia, was based on that kind of approach. When the plan was drawn up more than half a century ago the Civil War was still going on and the economy was severely dislocated. In order to step up farm output five-

fold or ten-fold the plan would have had to provide, for example, for an increase in the manufacture of such primitive implements as the wooden plough and also of peasant carts of the type that had predominated on the roads of pre-revolutionary Russia. This is the type of simple extrapolation that is now, fifty years later, practised by some contemporary futurologists. But actually the GOELRO programme was based on the idea of electrification of the whole country. Electricity was the pivot. It led to modern farm tractors, motor-cars, electric locomotives, and so on.

Not merely growth in quantity but changes in quality that will correspond to new, dynamic future are the most important element in forecasting. Dynamic principles, consumption standards and production techniques corresponding to future conditions and making full allowance for the water factor, including, for example, the transfer of some industries to a dry technology, are an inseparable part of progress. One of the jobs of the future will be to bring water consumption into line with the supplies of water in more or less large areas, such as subcontinents, taking into account the possibility of increasing the available amounts by regulating streamflow, diverting water from abundantly supplied areas to areas with a shortage, and other steps.

We do not limit ourselves to putting forward the idea of forecasting based on the dynamic pace of progress. We shall attempt to put the idea into practice by making some suggestions on matters of principle. The suggestions take into account the properties of water and the other components of nature with which water is connected, technological possibilities, and economic feasibility.

In any case, however, no matter how involved they are, the measures will be justified since there is no

substitute for water, particularly for human use and as a biological factor, especially as a factor in the production of food, both vegetable and animal. In our view, future-oriented water use demands that the two main principles be thoroughly revised. First, a stop must be put to the dumping of sewage into rivers and other bodies of water, even after treatment. Water is an unsuitable environment for the oxidation and purification of sewage. This also applies to the residue that remains in sewage even after it has been treated by the most modern methods. Second, the economy as a whole must do everything it can to reduce the amount of water used and prevent the formation of industrial sewage or any other effluents.

PUBLIC WATER SUPPLY

Water supply systems vary widely in purpose and in quality of water required.

Drinking water and water used in the food industry and some other industries must meet the highest standards. The same municipal water is also used for domestic purposes, to water foliage and streets and fight fires, and for certain industries which do not require much water, chiefly the light industries.

Industries that consume large amounts of water—for example, metal manufacturing and heat and power—constitute a separate water supply group. However, their high water requirements are relative, depending on the type of supply system. A *direct flow system*, that is, one in which the entire supply is drawn from a stream, lake, reservoir or groundwater basin, requires more water. In a *recycling system* the user draws only as much water from the source as he needs to replace the amount lost in the process of production.

First, let us consider water for domestic and other municipal purposes.

The municipal supply is piped into homes and is used to water foliage and streets, in the trade network, and in the food industry.

One person needs from two and a half to three litres of water a day, or about one cubic metre a year, for drinking and cooking. With the population of the world now at 3,600 million, the total requirements for these purposes come to a little more than 3.5 cubic kilometres annually.

If Muscovites used only drinking water, the Moscow water works would have to supply about 18,000 cubic metres of water a day or a little more than 6,500,000 cubic metres a year. Actually, the Moscow system provides about 200 times more water than that—nearly 1.3 cubic kilometres a year; this is almost 3,500,000 cubic metres a day, or about 600 litres per person, daily. The equivalent of a river with a discharge of more than 40 cubic metres per second flows continuously into Moscow's water mains.

This is less than the amount which flowed in the Moskva river before the Volga was linked up with it by a canal built in the 1930's. Now the Moskva river, together with the Volga water, has an average discharge of 50 to 60 cubic metres per second, which is only about 50 per cent more than flows through the Moscow water mains. Leningrad, with a population of 3,000,000, uses 1,700,000 cubic metres of water daily[41] (570 litres a day per person), or a little more than 0.6 of a cubic kilometre a year. This corresponds to a streamflow of 20 cubic metres per second. In Stockholm, daily consumption was 300 litres per person in 1950, while in Copenhagen it was 200 litres.[42]

A high level of urban water consumption is often regarded as an achievement and a sign of civilization.

Up to a point, this is indeed so. On the average, it is believed that 200 litres a day is enough to meet a person's domestic requirements. The food industry and trade network need about 100 litres a day per head of the population. All these purposes call for water of the highest quality that has been purified of bacteria and admixtures. About 100 litres per person goes to sprinkle the streets and to water foliage. The total is not more than 400 litres a day per urban dweller.

The amount used over and above 400 litres a day per person is accounted for by industrial enterprises, which do not necessarily require high-grade drinking water. A city with well-developed and highly water-consuming industries should have two systems, one supplying high-grade water for drinking and domestic use, and the other providing water for industry.

Paris, Hanover, Stuttgart, Frankfort-on-Main and a number of other big cities now have two separate supply systems. Some large plants in Moscow also have separate water mains. In future this way of saving drinking water will become more and more widespread.

There is a big gap between urban and rural water consumption per capita. In the cities, the world's average per person is 150 litres a day or 55 cubic metres a year; in the rural areas, it is no more than 50 litres a day, or 18 cubic metres a year.

The cities of the world have 1,200 million inhabitants and the rural localities 2,400 million. Calculated on the basis of the above-mentioned averages, annual total urban water consumption is roughly 66 cubic kilometres, while total rural consumption is 43 cubic kilometres (not counting water used for livestock), which makes about 110 cubic kilometres in all. Approximately 20 per cent of the municipal water sup-

ply—13 cubic kilometres—is lost, and 53 cubic kilometres of used, polluted water is returned to the rivers. Irretrievable water use in the rural supply is 30 to 35 cubic kilometres, with only 10 to 15 cubic kilometres returning to the rivers.

Urban and rural water supply systems produce about 65 cubic kilometres of sewage, of which about 60 cubic kilometres is discharged into streams and something like five cubic kilometres into the sea. If we assume that about half the sewage is treated, between 200 and 240 cubic kilometres of clean river water will be required to render that half, 30 cubic kilometres, harmless. Twice as much clean water, that is, between 400 and 500 cubic kilometres, is needed to render the untreated sewage harmless. Thus, between 650 and 700 cubic kilometres of clean river water is needed annually to purify all urban and rural sewage.

Hydroeconomic calculations do not take this type of water use into account as a rule. There is no particular reason to do so, from the consumer point of view, except for the important factor of quality. It is true that the turbines of hydropower stations function just as well on polluted water. Nor do irrigation and a number of other economic spheres suffer from polluted water. But that approach is impermissible from the environmental viewpoint. Drinking water, recreation on rivers, lakes and reservoirs, water for hygienic purposes, sports and as the habitat of fresh-water fish, and other factors that comprise the water component of the environment, demand that some of the principles of the economic water balance be revised. First of all, it is necessary to estimate the amount of river water that goes to purify sewage discharged into streams and other bodies of water.

The 650 to 700 cubic kilometres of river water needed to purify sewage after domestic and other municipal

use should therefore be entered on the debit side of the balance-sheet.

Plans for the future must take into account a rise in water consumption. Since increased urbanization will gradually bridge the gap between urban and rural use, we can take 400 litres a day or 150 cubic metres a year as the average per capita standard for the entire population of the world. If, as estimated, the world's population reaches 6,300 million by the year 2000,[43] total water use for domestic needs will grow to the enormous amount of about 920 cubic kilometres a year. That is almost seven per cent of the volume of the stable runoff of all the world's rivers and 25 per cent of the total annual streamflow. The above figures, it should be remembered, refer to high-grade water.

The irretrievable share of the water used for domestic and municipal purposes in the year 2000 will probably not exceed the 20 per cent it does today, making an annual total of 180 cubic kilometres. We must clearly realize, however, that the water remaining after use is sewage. If this sewage is discharged into waterways, even after expensive and much better artificial cleaning than is possible today, the volume of contaminated streamflow will increase several times over, and rivers will be turned into sewers.

A large number of rivers will cease to be sources of water. People will find themselves living on the banks of lifeless streams. In other words, the evil is not so much large-scale water use as the discharge of sewage into waterways. The conclusion to be drawn is that the pouring of sewage into streams, lakes and reservoirs must be stopped.

This is the best way of preventing water resources from becoming exhausted. In the late 20th and early 21st century it will be more necessary than ever to prevent the discharge of sewage into streams, lakes

and reservoirs. The supply of water for drinking and domestic uses will increase in proportion to population growth. We can look forward to a more economical use of water in irrigation farming, power generation and other industrial fields by reducing consumption per unit of output or, in some cases, switching over to dry production. But this kind of approach is impossible when it comes to domestic and some other municipal water supplies. People's water requirements have to be satisfied to the full. We cannot plan on saving water here. Four hundred litres of water a day is evidently the minimum one person will need in future, and this minimum cannot be reduced.

However, water should be economized in other ways. Defective plumbing leads to a substantial loss of water. One leaking tap may let through as much as 100 cubic metres in a year. This is comparable to the amount one person uses in the course of one year. Every effort must be made to prevent such losses. But the chief way to economize, as we have said, is to stop discharging sewage into waterways. Below we shall show how the use of municipal sewage for irrigation or in heat and power production and other industries which do not require top-grade water partly solves the problem of treatment and is economically profitable.

Rough estimates show that the traditional water resources—rivers and groundwater—are fully capable of meeting the needs of between 60,000 million and 100,000 million people, as well as of industry.

The population of the world may not reach such a magnitude. But these estimates indicate the tremendous promise held out by improving ways of using and conserving water resources.

Are these estimates consistent with the present situation? It is true that with a population of 3,500 million there is a water shortage in many parts of the

world. Yet we insist that even if the population were to increase 20 or 30 times over, the traditional sources of water would suffice.

The crux of the matter is that today's water management principles are largely obsolete. They came into being at a time when the water-management balance was not strained and water needs were, as a rule, met without any special effort. If man continues to follow these principles the water resources will not last long. In fact, they might be exhausted within the next three or four decades.

Therefore, man must radically improve the principles of water use and conservation. First, sewage must not be dumped into streams or other waters. Second, industry must reduce its water consumption; water-consuming industries must be turned into non-water-consuming industries by developing new production methods that require a minimum of water. Third, water used in industry should be recycled. Fourth, the amount of water used per unit of farm output should be reduced.

It is extremely important in general to bring water requirements into conformity with the supplies in a more or less large area, such as a subcontinent, for example. We have to remember, of course, that the need for water may arise in places where it is in short supply. This applies especially to the mining industry. On the whole, however, water resources are a major factor in industrial siting.

All this can be gradually accomplished within the next two or three decades. The above steps do not, however, exhaust all the possibilities for a more remote future. In the distant future sewage will probably be treated by distillation or regeneration, after which the water will be re-used. At present these types of treatment are too power-consuming and costly.

In the distant future synthetic food will evidently hold such a large place in the human diet that agricultural water needs will drop. Today, three-quarters of the water used goes for irrigation. Irrigation water, plus that used in non-irrigation farming, amounts to six times more than the water used for all of man's other needs. We must bear in mind, though, that the amount of vegetation on earth cannot be reduced since it fulfills the vital function of enriching the atmosphere with oxygen.

Technological progress, which is unlimited, will provide additional reserves to meet a continued growth of water consumption. Efficient and economical ways of using the water of polar glaciers and of desalinating sea water will ultimately be found.

Introduction of *water recycling systems* at factories and heat and power stations is an important element of technological progress. What this economical and efficient method of utilizing water resources means can be seen from the example of thermal power plants. In the cooling of the turbogenerators these stations lose by evaporation about three litres of water per kilowatt of generated power. Stations with a capacity of 1,000,000 kilowatts (and there are quite a few such stations in the Soviet Union and other countries) generate approximately 8,500 million kilowatt-hours of electricity a year. Turbogenerator cooling evaporation losses at a station this size amount to 0.8 cubic metre per second, or approximately 25,000,000 cubic metres a year. This is why thermal power plants rank among the largest water users.

Such losses occur at the most modern stations having recycling systems and at plants supplying heat for homes and factories. At stations using a direct flow system, and there are still many of these, water intake is about 25 times over. In this case a 1,000,000-

kilowatt station will use as much as 625,000,000 cubic metres a year (compared to 25,000,000 cubic metres when a recycling system is employed), i.e. 20 cubic metres per second. By comparison, a fairly large river has a mean annual discharge of some 35 to 70 cubic metres per second.

If the water used to cool turbogenerators is returned to the river there would seem to be no loss. But hot water kills organic life in streams not only because of the high temperature but also because water loses oxygen when it is heated, and the oxygen is replaced only after the water has travelled a long way downstream. Biological processes cannot proceed normally until the water's oxygen content is restored to normal. For this reason water that was used to cool turbogenerators at power plants should not be discharged into rivers and lakes.

Today, with the world's thermal power stations generating 3,000,000 million kilowatt-hours of electricity, the irretrievable evaporation losses during cooling of the turbogenerators add up to roughly 10 cubic kilometres a year.

This is a theoretical estimate showing the minimum amount of water that should be used to keep thermal power stations operating. Actual consumption is substantially greater, chiefly because a large number of plants do not have recycling systems. Approximately 250 cubic kilometres of water a year is removed, mainly from rivers, lakes and reservoirs, for cooling purposes, bringing the irretrievable loss to 15 cubic kilometres annually. This loss is not particularly great, but the release of 235 cubic kilometres of hot water into streams and lakes is highly injurious to organic fresh-water life and makes it more difficult to use these sources in the drinking-water system.

In our forecast of water resources in the year 2000 we

assume that the world's power stations will generate approximately 17 times as much electricity as they do today. This follows from the assumption that the world's industrial output will increase 14 to 15 times over, and that growth in power output will exceed industrial expansion by about 20 per cent. Hence, some 50,000,000 million kilowatt-hours of electricity will be generated.

If the amount of water used by thermal power stations increases proportionally, with partial improvement in water supply, losses will rise to 200 cubic kilometres and water intake to 3,100 cubic kilometres annually. That is impermissible, since the discharge of corresponding amounts of hot water into streams and lakes after using it to cool turbogenerators would contaminate at least 7,000 cubic kilometres of running water, or more than 20 per cent of the aggregate flow of all the rivers on earth and half of the stable flow. Since there is a progressively growing demand for water for other purposes so much thermal pollution might prove catastrophic.

In view of the limited resources, the provision of water for thermal power stations in future must be based on more rational principles.

Water expenditure per kilowatt-hour of generated electricity can be almost halved to 1.6 litres, experts say, thanks to greater thermal power plant efficiency[1]. Since nuclear power stations use relatively more water we shall take two litres as the average expenditure per kilowatt-hour. This will bring the annual water loss in producing 56,000,000 million kilowatt-hours of electricity to 100 cubic kilometres, an increase of only seven times as compared with a 17-fold increase in the amount of electrical energy generated.

The goal for the future is to switch all thermal power stations to recycling systems. Then the intake

from rivers and lakes to cool turbogenerators will not be much more than the irretrievable water losses. Thermal power plant water intake will drop by almost half as compared with today.

Another way of economizing river water is by using sea water to cool turbogenerators. The hitch is that evaporation leaves the salt behind. Nevertheless, sea water is now being used at some stations for cooling and in future the present problems will undoubtedly be solved.

A practically untapped reserve is the use of treated municipal waste waters as a source of water for thermal power stations.

Industry's water demands are growing not only because of rapid industrial expansion as such but also because of an increase in the amount of water used per unit of output. It takes about 250 cubic metres of water to produce one ton of cotton fabric; one ton of man-made fibre requires between 2,500 and 5,000 cubic metres. The chemical industry consumes extremely large amounts of water: about 1,000 cubic metres is needed to produce one ton of ammonia, and 2,000 cubic metres for one ton of synthetic rubber. The nonferrous industry has a high water-to-unit-of-output ratio: 4,000 cubic metres of water is used to smelt one ton of nickel. Compare this with the 180 to 200 cubic metres of water—20 times less—required in the smelting of one ton of pig iron.

The rapidly expanding oil industry also uses a great deal of water. It consumes 35 cubic metres to refine one ton of crude oil. But at some refineries, where different processes are employed, the amount of water used drops to 0.5 cubic metre per ton of oil. Irretrievable water consumption in the chemical, oil refining and pulp and paper industries of the United States amounted to more than three cubic kilometres in 1960.

This was 55 per cent of total industrial irretrievable water use. Two-thirds of the industrial water in the United States is consumed by the three above-mentioned industries.

We have cited these figures to show the prominent place the three most water-consuming and most rapidly-growing industries hold in the overall picture of water use.

A total of about 400 cubic kilometres of water is now required annually by the industrial enterprises of the world. Since roughly half of them have recycling systems, only about 200 cubic kilometres is drawn from streams, lakes and groundwater. Total annual irretrievable consumption in industry is estimated at 40 cubic kilometres.

None of these figures is very large compared with the available resources. Nevertheless, factories and mills in a number of industrial regions in Europe and North America are threatened with a water shortage. This is due chiefly not to uneven distribution of water resources and industries but to the fact that the water used in industry, particularly by chemical works and pulp and paper mills, becomes so polluted that treatment is not always sufficiently effective. The result is that about 160 cubic kilometres of industrial waste water is dumped into streams, contaminating at least 2,000 cubic kilometres of natural river water.

Since far from all waste water is cleansed before being poured out, actual river pollution is still greater. At least 4,000 cubic kilometres of river water is polluted annually. This is more than 10 per cent of the streamflow of all the world's rivers and about 25 per cent of the streamflow of the rivers in the most highly industrialized regions.

What will happen in 30 or 40 years, when industrial output is far greater? Let us assume that by the year

2000 industry throughout the world will have reached the level attained today by the most economically advanced countries. This will mean an approximately 14- or 15-fold world industrial growth in the next three decades.

Industrial expansion throughout the world naturally depends on social, scientific and technological factors into which we cannot go in detail here. The 14- or 15-fold increase which we assume here is a big one, but experience shows that it is entirely feasible. In the Soviet Union, for example, total production in the first 50 years of the Soviet system increased 66 times over. Moreover, far from all of the 50 years were devoted to construction. About 20 years of this time was taken up by the Civil War, the Second World War and the reconstruction periods. Actually, the 66-fold production increase was achieved in 30 years. We obviously cannot count on industrial production throughout the world growing at that rate. Industry in the United States could expand more than five-fold by the year 2000, American experts say, although such growth is considered exaggerated for that country.[1]

As we see, a 14- or 15-fold increase in the world's industrial production within 30 years is fully possible. On the basis of this growth rate we can roughly estimate industrial water requirements. We realize that the 14- or 15-fold expansion may take place sooner or later than the year 2000, but this is not so important in estimating future water resources, which will eventually have to meet those increase requirements anyway. They will also, of course, have to meet all other water needs.

Calculating on the basis of present-day practices, we find that after a 14- or 15-fold growth in output total annual industrial water consumption will amount to approximately 6,000 cubic kilometres by the year

2000, with a water intake of up to 3,000 cubic kilometres. Irretrievable use will be about 600 cubic kilometres, and the huge volume of some 2,400 cubic kilometres of sewage will be discharged into waterways annually. If we assume that all sewage will be treated before it is dumped, and treatment standards will be much higher, at least 24,000 cubic kilometres of pure running water will be needed to dilute the industrial sewage. Since there will also be other water users, sufficient resources for such a large amount of water for industry would not be available.

This catastrophic situation must be averted—and it *can* be averted by taking the appropriate steps.

These include reducing the amount of water consumed per unit of output and, where possible, switching industries to dry processes. Work has started in this direction and in some cases has already yielded good results. New processes in oil refining, for example, are lowering water consumption rates.

But while the rate of industrial water use is reduced, new industries that consume water in large amounts will arise. We may therefore assume that the level of consumption per unit production will, on the average, remain unchanged, although the structure of industrial use will change considerably. This being the case, the annual irretrievable industrial use will rise to 600 cubic kilometres after output increases 14- or 15-fold. Even if substantially more water is required the available resources will be able to supply it.

But to keep the industrial water balance within these limits most factories will have to re-use their water. This complicates matters but it can be done. Many factories in the Soviet Union are beginning to recycle. In the industrial German Federal Republic, where water resources are limited, 92 per cent of all enterprises have recycling systems. So does 50 per cent

of United States industry. Re-using water in industry means that no wastes reach the rivers. The amount of water allocated to a plant is used over and over again after treatment. Additional water is supplied only to replace what is lost, which averages about 10 per cent of the total used.

It is hard to imagine, though, that the supply could be kept down strictly to the amount lost irretrievably. This would, of course, be the most economical and efficient arrangement, but some inescapable factors have to be taken into account. We refer mainly to the used water that cannot be effectively cleaned and must be distilled or regenerated, eliminated through evaporation, or used for irrigation if not harmful to plant life. In any case, we have to add 15 to 20 per cent to the 600 cubic kilometres irretrievably consumed in industrial production. That brings the total amount for industrial needs to about 700 cubic kilometres. Intake from rivers and groundwater sources will then increase only 3.5-fold with a 14- or 15-fold industrial growth. A great saving in resources will come when industrial wastes are no longer dumped into streams, lakes and the sea, for they pollute a tremendous amount of pure natural water.

The figures on supply today and in future presented in Table 19 graphically illustrate the effectiveness of improved principles of using and conserving water resources.

If the practice of discharging a significant part of used water into rivers is continued, the most conservative estimates show that more than 6,000 cubic kilometres of waste water would annually contaminate at least 38,000 cubic kilometres of river water even after treatment by better methods than are now used. This would actually exhaust all the water resources of the world's rivers. No flowing fresh water would be left

TABLE 19

USE OF WATER IN WATER SUPPLY SYSTEMS (KM³ ANNUALLY)

Item	Today				In future							
					if present-day water use principles are followed				if more rational water use principles are followed			
	Intake	Irretrievable loss	Waste water dumped	Volume of river water polluted by wastes	Intake	Irretrievable loss	Waste water dumped	Volume of river water polluted by wastes	Intake	Irretrievable loss	Waste water dumped	Volume of river water polluted by wastes
Domestic and municipal	110	45	65	680*	920	180	740	6,000	950	950**	0	0
Animal husbandry	40	30	10	300	150	100	50	600	100	100	0	0
Power stations	250	15	235	600	3,100	200	2,900	7,000	45	45	0	0
Industry	200	40	160	4,000	3,000	600	2,400	24,000	410***	410***	0	0
Totals	600	130	470	5,580	7,170	1,080	6,090	37,600	1,505	1,505	0	0

* Not counting the volume of polluted sea water.

** Of which 200 cubic kilometres (approximately 20 per cent) is for domestic and other municipal purposes, 450 cubic kilometres for irrigation of farm fields and 290 cubic kilometres for power stations and other industrial uses after treatment.

*** Not counting 290 cubic kilometres of re-used waste waters.

for drinking, for the fishing industry, recreation and other vital purposes. Finally, the world's fresh water must be pure in order to ensure a suitable environment for man. In short, if the present principles of utilizing water resources remain unchanged the rapid rise in water consumption will lead to disaster.

A water shortage would become acute in the nineties of this century (in some parts of the world this might happen even earlier). People would face the bleak prospect of living along rivers that had become sewers.

When sewage ceases to be pumped into streams, and industry, including the power industry, starts re-using water, the picture will be quite different. In the year 2000 irretrievable use in the municipal water system will then be 400 per cent greater, and in all types of water supply about 40 per cent greater than if sewage continued, in the main, to be discharged into rivers. While total irretrievable water use today is about 130 cubic kilometres, or about 0.3 per cent of total streamflow, sewage pollutes 5,600 cubic kilometres of streamflow, which equals 40 per cent of the stable flow.

The two forecasts in Table 19, one based for the most part on contemporary principles of water use and conservation, the other envisaging that sewage will no longer be dumped into waterways, are extremes. Actual development will proceed somewhere in between, evidently closer to the second forecast. It is quite possible that in water-rich, sparsely populated and economically underdeveloped areas the rivers will still be capable of purifying themselves in the year 2000. But in the final analysis, the dumping of wastes will have to be given up everywhere.

The reader should bear in mind that the figures in Table 19 are rough approximations, but they provide

some idea of water management trends that must be taken into account today.

IRRIGATION

The nearly 220 million hectares of irrigated land in the world produces about as much crop as the 1,200 million hectares of non-irrigated land. In other words, irrigated land is five or six times more productive, on the average, than non-irrigated land. Water plays a big part in this, of course, but so do other factors, particularly climate and fertilizers.

Most of the irrigated land is in warm regions, where two and even three crops a year are grown on sizable areas. This is far less common on non-irrigated land because of either the dry or cold weather.

Between 12,000 and 14,000 cubic metres of water is used in a year, on the average, to irrigate one hectare of land. A total of 2,500 cubic kilometres of water is taken annually from streams and groundwater basins for irrigation. This is more than six per cent of the world's total annual river discharge and almost 18 per cent of stable streamflow. Irrigation farming is the biggest of all water consumers.

An average of at least 25 per cent, or 600 cubic kilometres, of water taken from streams and groundwater for irrigation goes back into the waterways or into groundwater. Annual irretrievable water losses in consumption by irrigation farming thus amount to 1,900 cubic kilometres.

The irrigated area in the Soviet Union has increased from 4,000,000 to 10,000,000 hectares in Soviet times. Besides, most of the primitive networks built before the Revolution have been modernized. Such large engineering projects as the Great Ferghana Canal, along the left bank of the Syr Darya, and the Kara Kum

Canal, which starts from the Amu Darya river and runs across the whole of the Turkmenian Republic to the Caspian Sea, have been carried out.

A series of reservoirs that will help to make irrigation farming independent of natural fluctuations in streamflow are now under construction in Central Asia. Work is well advanced on the Toktogul hydropower plant on the Naryn River, with a reservoir having a total available storage of about 13 cubic kilometres. The large Mingechaur reservoir has been built on the Kura River in the Caucasus. Although the technical equipment and efficiency of Soviet irrigation farming rank among the highest in the world, much more development and improvement is possible, as, for that matter, in other countries too.

In a number of cases the efficiency of irrigation systems is still very low. In Central Asia, less than two thirds of the water diverted from rivers for irrigation actually reaches the fields. The rest is lost in the canals through evaporation and seepage, part of it returning to the rivers via groundwater discharge.

Irrigation efficiency can be raised to between 70 and 80 per cent by preventing seepage from the canals and by building penstocks to carry water to the fields. And that is obviously not the limit of efficiency.

Research has revealed that sometimes substantially more irrigation water is used than the plants require. In such cases the water table rises, plants are suppressed on waterlogged soils, and crop yields drop. Significantly, the highest cotton yields in Central Asia are obtained on farms which irrigate economically. Excessive water leads to salination of the soil and a decline in its fertility. Expensive drainage networks are built to help remove excess water from the fields and thus prevent them from becoming waterlogged and salt-ridden.

The amount of water which plants give off in trans-

piration, is much less than the amount of irrigation water used. Experiments in the Hungry Steppe by V. A. Kovda[44] showed that out of 12,160 cubic metres per hectare of water used on a cotton field during the vegetation period, 6,600 cubic metres (54 per cent) went into evaporation and 5,560 cubic metres (46 per cent) into transpiration.

Another experiment showed that out of 12,240 cubic metres of evapotranspiration per hectare, 6,330 cubic metres (52 per cent) was evaporation and 5,910 cubic metres (48 per cent) was transpiration. Investigations carried out by the present writer on a field of irrigated wheat in the southern reaches of the Volga revealed that evaporation accounted for 1,930 cubic metres of water, or 49 per cent, out of an evapotranspiration total of 3,970 cubic metres. (See Table 10.) Since the method used in studying the structure of evaporation and transpiration is fairly involved, research is being conducted on a limited scale. But the available data make it clear that a great deal of water can be saved by reducing evaporation from irrigated land.

We have found that shelter belts, by reducing evaporation, enable less irrigation water to be used while significantly higher crop yields are obtained.[9] A minimum of 20 to 30 per cent less irrigation water is needed in Central Asia, and at least one-third less is needed in the south-eastern steppe zone of the European part of the Soviet Union. This means that one or two applications of 1,000 to 1,200 cubic metres of water per hectare out of six can be eliminated in Central Asia, and one application out of the three required where there are no shelter belts can be eliminated in the south-east. Other methods will doubtlessly be found to control evaporation in irrigation.

Mechanized irrigation also leads to a big water sav-

ing. An example is the use of sprinklers. A more uniform distribution of water allows the amount used to be halved compared with manually controlled irrigation.

All this shows the great possibilities of economizing water in irrigation farming. It would probably be no exaggeration to say that in future 30 per cent less water will be diverted from streams and groundwater sources for irrigation, that is, 9,000 cubic metres per hectare instead of the 12,000 to 14,000 cubic metres per hectare today.

To estimate the scale of irrigation farming in the year 2000 or so, we must determine, if only approximately, how much farm produce will have to be grown to meet man's food requirements.

Today, grain crops are grown on 160 million hectares of irrigated land. The remaining 60 million irrigated hectares produce non-grain crops (30 million hectares) and industrial crops (30 million hectares). The average grain yield on irrigated land (taking into account the fact that two or three crops are harvested annually in some areas) may be taken as three tons per hectare, making 480 million tons a year. The yield of non-grain crops (vegetables, melons, etc.) is about 15 tons per hectare.

About 1,050 million hectares of non-irrigated land are planted annually to food crops, including 430 million hectares to cereals, which, with an average harvest of about 0.8 ton per hectare, produce 340 million metric tons of grain. Non-grain crops take up about 620 million hectares, each of which yields 2.5 tons of foodstuffs. In terms of grain this would be about 0.5 ton per hectare, or 310 million tons from the entire territory planted to non-grain crops.

To sum up, the world's annual production of food, in terms of grain, amounts to 570 million metric tons

on irrigated land and 650 million tons on non-irrigated land. The total is 1,220 million tons, or 360 kilograms a year per person (this figure includes feed for livestock). However, it is estimated that almost 1,500 million people are underfed.[45]

Eight hundred kilograms of grain a year per person, twice as much as the present figure, is considered a normal amount.

To supply a population of 6,300 million, annual food production in terms of grain must be approximately 5,000 million tons, or almost four times the present amount. This is the goal which farming, both irrigated and non-irrigated, must reach.

If we assume that irrigation farming must account for 40 per cent, or 2,000 million tons, of grain, and that yields will rise to four tons per hectare, the irrigated area will have to be enlarged to 500 million hectares.

Above we considered the question of the future irrigation rate. Water intake can be reduced from 13,000 to 9,000 cubic metres per hectare, and the amount supplied to each hectare from 9,000 to 8,000 cubic metres. Then the amount diverted annually from streams and groundwater sources for an irrigated area of 500 million hectares would be 4,500 cubic kilometres, and total irretrievable water use for irrigation would be 4,000 cubic kilometres.

Remember that we have set aside 450 cubic kilometres of sewage for irrigation.

Sewage is rich in organic fertilizers and is therefore valuable in irrigation, especially in growing the fodder crops needed for suburban meat and dairy farming. A lower irrigation rate is set in the case of sewage than in conventional irrigation. This is because sewage irrigation will become widespread in the temperate zone as well, where less water is needed than in south-

ern regions to grow the same amount of produce. Sewage irrigation must be controlled to prevent water from flowing from the fields into streams. Experience shows that about 6,000 cubic metres of sewage per hectare is needed for irrigation. There will thus be a sewage irrigation area of 75 million hectares and an area of 425 million hectares irrigated with pure water. By using sewage for irrigation the amount of pure water diverted from rivers and groundwater sources can be reduced to 3,800 cubic kilometres and irretrievable water use lowered to 3,400 cubic kilometres.

Table 20 sums up what has been said about the use of water resources for irrigation today and in future.

TABLE 20

USE OF WATER TO IRRIGATE FOOD CROPS

	Irrigated area (million hectares)	Irrigation rate (cubic metres per hectare)		Total annual use		Grain crop		Water used per ton of grain (cubic metres)
		From sources	Irretrievable loss	From sources	Irretrievable loss	Total crop (million tons)	Per hectare (tons)	
Present	190	13,000	9,000	2,500	1,900	570	3.0	3,300
Future including:	500	8,500	7,700	4,250	3,850	2,000	4.0	1,900
pure water	425	9,000	8,000	3,800	3,400	1,700	4.0	2,000
sewage	75	6,000	6,000	450*	450*	300	4.0	1,500

* Water remaining after use as drinking water and for domestic purposes.

Total production of food crops will increase 3.3-fold with a little more than a 2.5-fold increase in the irrigated area, an increase of 1,500 cubic kilometre, or

65 per cent, in the amount of water diverted from rivers, and a 100 per cent increase in irretrievable water use, which will reach 1,700 cubic kilometres.

Table 20 deals with food crops, but 30 million hectares of irrigated land are now planted to industrial crops. It is unlikely that this area will be enlarged in future, since the trend is towards using synthetic fibres to replace vegetable fibre. Assuming that the amount of irrigation water required to grow industrial crops is about the same as that needed for food crops, 2,800 cubic kilometres of water now has to be diverted from rivers and groundwater sources to irrigate 200 million hectares, with an irretrievable water use of 2,100 cubic kilometres. In future an intake of 4,400 cubic kilometres will be needed to supply water for 530 million hectares of crops, including industrial crops, while irretrievable use will amount to 4,000 cubic kilometres.

Every effort must be made to reduce the amount of irrigation water per ton of farm produce. The amount required today exceeds 3,000 cubic metres per ton for food crops, and up to 1,500 cubic metres per ton if waste waters are used. If the expenditure of water per ton of grain and the irrigation rate were to remain the same as they are today, the irretrievable use for irrigation from rivers and groundwater sources would reach 6,600 cubic kilometres, that is, would be almost two and a half times as much as it is today.

This shows how important it is to use irrigation water more efficiently. The same applies to the use of water in non-irrigation farming.

WATER IN NON-IRRIGATION FARMING

In present-day water management the amount of water used to grow food and industrial crops on non-irrigated land is not calculated. The only reason is that

this use goes unnoticed since there is no direct intake from streams and groundwater sources, as in irrigation farming. Agronomic practices provide ploughland with soil moisture. In regions with insufficient or variable moistening various water-retention measures are employed, but their influence on the water balance is usually not calculated.

That such an approach is unjustified can be seen from the fact that about 250 cubic kilometres of water is used on the arable land of the Soviet Union to produce food and industrial crops. This is more than is consumed by all water supply and irrigation systems combined. Moreover, the amount used is growing steadily as scientific farming methods improve and yields increase.

In recent decades at least 15 to 20 cubic kilometres of additional water has been supplied annually to arable land in the drought-afflicted areas of the European part of the Soviet Union by trapping surface runoff. The amount of water used to produce crop vegetation has increased correspondingly. Is this much or little? Does this use affect the hydroeconomic balance? We are so accustomed to talking about cubic kilometres of water that we tend to forget that one cubic kilometre is equal to 1,000 million cubic metres. A little more than 12 cubic kilometres of water is used up annually by all the cities and industries of the Soviet Union. This is less than the amount annually retained on the arable land in the southern regions of the European part of the country.

Actually, soil moisture is increased at the expense of streamflow. The connection is obvious: non-irrigated fields receive additional moisture when runoff is arrested. But it is runoff that creates river flood flow. When more water is retained on the fields less of it reaches the rivers. Does this redistribution of water

resources—an increase in soil moisture at the expense of river flood flow—benefit man? Yes, because *crop production is one of the best uses to which water resources can be put.* Other types of use, such as navigation, hydropower generation and some types of industrial production can be replaced by less water-consuming methods. Navigation can be replaced by overland transport and hydropower plants by thermal stations; some industries can be switched to "dry" production methods.

But nothing can take the place of water in plant-growing. Any increase in total harvests involves an increase in the water required, although not a directly proportional one. As in irrigation farming, improved agricultural methods reduce water consumption per unit of plant matter, but total water use grows.

Tomorrow's water use in crop production can be roughly calculated by the following method.

First we determine the future per-hectare grain yield and the increase in the area under food crops. In all probability, yields will approximately treble and reach 1.8 metric tons per hectare. Better farming methods, extensive use of fertilizers and the development of higher-yield crop varieties will all contribute to this.

On the basis of the above we see that the world's arable land will have to be brought up to 1,700 million hectares. In our further estimates we proceed from the amount of water needed to grow above-ground plant matter. With today's average grain yield at 0.62 ton per hectare the weight of plant matter, including stalks, is estimated at about two tons per hectare. If the transpiration rate is 300, meaning that 300 cubic metres of water is transpired to produce one ton of plant matter, transpiration accounts for the use of 600 cubic metres per non-irrigated hectare.

Total water consumption per non-irrigated hectare, remembering that evaporation amounts to one half of the total, reaches 1,200 cubic metres. This adds up to 1,260 cubic kilometres from a total area of 1,050 million hectares.

We shall consider that when, in future, 3,000 million tons of cereals are grown on non-irrigated land there will be four tons of above-ground plant matter per hectare.

Improved farming methods will help to reduce the transpiration rate from 300 cubic metres per ton of above-ground plant matter to 250 in future. This is fully possible since there are many cases today where the transpiration rate in cereal production does not exceed 250. With this rate, transpiration will reach 1,000 cubic metres per hectare. If we put evaporation at 500 cubic metres per hectare, or somewhat less than the present figure, we obtain a total of 1,500 cubic metres of water per hectare consumed by transpiration and evaporation.

With an area of 1,700 million hectares under food crops the total water use on non-irrigated land will amount to about 2,500 cubic kilometres a year instead of the present 1,260 cubic kilometres, that is, it will almost double. (See Table 21.)

Water consumption per hectare of arable land will increase by 300 cubic metres, but 1,110 cubic metres less will be needed to produce one ton of grain.

It should be borne in mind that the above estimates of water use on non-irrigated land refer only to food crops. We must add to them the water used on 120 million hectares of industrial crops. Assuming that industrial crops require the same amount of water as grain crops, about 140 cubic kilometres of water is now consumed annually in the production of industrial crops. This will increase to 180 cubic kilometres in

TABLE 21

APPROXIMATE WATER USE IN PRODUCING FOOD CROP PLANT MATTER ON NON-IRRIGATED LAND (IN TERMS OF GRAIN)

	Grain harvest		Arable land (millions of hectares)	Amount of water needed to produce plant matter		
	Total (mln tons)	Per hectare (tons)		Total (cu km)	Per hectare (cu m)	Per ton of grain (cu m)
At present	650	0.62	1,050	1,260	1,200	1,940
In future	3,000	1.80	1,650	2,500	1,500	830
Difference	+2,350	+1.18	+600	+1,240	+300	−1,110

future. Overall water use for industrial crops on non-irrigated land will increase from today's 1,400 cubic kilometres to 2,680 cubic kilometres, or by nearly 1,300 cubic kilometres.

There will also be an increase in the amount of water used to make meadows and pastures, covering 2,600 million hectares, more productive. If the increase is 100 cubic kilometres, the total water used on non-irrigated ploughland and on meadows and pastures will then come to about 1,400 cubic kilometres.

Now let us see where the water for additional evapotranspiration from arable land will come from.

In regions with excessive soil moisture, increases in the amount of water used to produce vegetation will come from the soil. But in regions with insufficient moistening the higher crop yields will be achieved with water obtained from other sources.

One source, as we have mentioned, is surface runoff. In the arid zone, surface runoff is actually a loss

of water from arable land. Moreover, it washes away topsoil and causes soil erosion. Farmers try to prevent this waste by channelling surface runoff into the soil.

Extensive autumn ploughing and other improved farming methods have increased the soil water resources on arable land in the steppe and forest-steppe regions of the Soviet Union by between 15 and 20 cubic kilometres a year. These figures are expected to grow to some 30 or 40 cubic kilometres by 1980. This involves a corresponding decrease in flood runoff.

The world's arable land is divided about evenly between well-moistened and arid territories. Therefore, half of the 1,400 cubic kilometres of water that will be added to the amount used to grow plant matter on non-irrigated land will be accounted for by regions with sufficient moisture and half by arid areas, where the surface runoff augments soil water resources. Consequently, an increase of 700 cubic kilometres of water a year for moistening of the arable land in arid regions will lead to a corresponding reduction in the river discharge there.

This is not a large amount for the globe as a whole. But for some drought-afflicted areas the use of water to produce plant matter represents an appreciable part of the balance-sheet.

HYDROPOWER AND NAVIGATION

While power generation and navigation on rivers and lakes do not, in the main, remove any of the running water they use, there is, nevertheless, a loss of water through evaporation from the reservoirs that are formed behind most power dams. Reservoirs used to be built to keep rivers navigable in low water periods and to regulate streamflow for irrigation. Today they are often built as part of hydropower projects. The Minge-

chaur reservoir on the Kura river in the Caucasus, the Nurek reservoir on the Vakhsh river in Central Asia, the Aswan reservoir on the Nile and the reservoirs on the Colorado river are examples of projects designed both to produce electricity and provide water for irrigation. Reservoirs for irrigation only or for navigation only are now comparatively rare. In almost all cases the head of water created by dams is also used to generate electricity.

In 1960-1961 the total available storage of the world's reservoirs was 2,050 cubic kilometres. Of this volume 358 cubic kilometres belonged to the Soviet Union[16] and 343 cubic kilometres to the United States[1]. Above we cited recent data according to which the flow regulated by reservoirs exceeds 1,800 cubic kilometres a year.[19] More water evaporates from reservoirs than from the land that was flooded to form them. Total water loss due to increased evaporation on the chains of Volga, Kama and Dnieper reservoirs and the Tsimlyanskoye reservoir on the Don amounts to about 10 cubic kilometres a year. These reservoirs cover an area of about 35,000 square kilometres. The level of increased evaporation amounts to about 300 millimetres.

Total evaporation from the world's reservoirs has been estimated at some 160 cubic kilometres a year. Since their total area is about 300,000 square kilometres, the evaporation loss is equivalent to a water layer of 530 millimetres. The actual amount may be slightly more; at any rate, hardly less than an average of 600 millimetres, or approximately 180 cubic kilometres a year. Although that is equivalent to only one per cent of the stable flow of the world's rivers, it is roughly 80 cubic kilometres more than the present irretrievable use of water in all types of water supply systems (see Table 19 on p. 131). These losses are bound

to be still more appreciable in the water management balance in view of the construction of more reservoirs in future.

Eventually, the entire flood discharge of the rivers will have to be regulated by reservoirs and other means. But this will hardly be either possible or necessary towards the turn of the century. It will evidently suffice to build, within the next thirty years, reservoirs with a total available capacity of 4,000 to 5,000 cubic kilometres. This will be two and a half times more than the available storage of all existing reservoirs. Such storage will allow another 3,500 or so cubic kilometres of flood water to be regulated.

But the principle of siting reservoirs should be different from what it often is today. For more efficient hydropower generation, dams and reservoirs are now built where streamflow is concentrated and will yield large amounts of electrical energy, that is, chiefly in the lower reaches of rivers. Since the main role of reservoirs is to regulate rivers for multiple water-management purposes, it would be much more advisable to build them in the upper reaches. On large rivers a reservoir should have only as much capacity as needed to control the part of the flow that cannot be controlled by reservoirs situated on tributaries or in the upper reaches. If this approach were followed the capacity of reservoirs in the lower reaches would be minimal, thus saving land resources from the unnecessary but inevitable flooding that occurs when reservoirs are built to control the entire streamflow in order to generate electrical energy.

As land increases in value, steps should be taken to reduce to the minimum the area occupied by reservoirs, which have often been built on too grand a scale.

In future, one cubic kilometre of available storage should require the flooding of about 120 square kilo-

metres instead of the 150 square kilometres up until now. In that case the new reservoirs to be built by the year 2000 would cover an area of some 600,000 square kilometres and, together with the now existing reservoirs, whose area will gradually be reduced by damming off the shallow sections, will total 850,000 square kilometres. The available capacity of all reservoirs will be about 7,000 cubic kilometres.

Annual evaporation losses from reservoirs, compared with evaporation from the territory before it was flooded, will increase 180 per cent and reach about 500 cubic kilometres by the year 2000. Reservoir evaporation is considerable and must be reckoned with in the water management balance. But these losses and the loss in land resources—kept to a minimum, of course—cannot be regarded as an obstacle to the building of reservoirs. Storage lakes are vitally necessary, and they will play a steadily growing part in refashioning the water cycle. Reservoirs will help to increase stable flow resources from 14,000 cubic kilometres to 17,000 or 18,000 cubic kilometres.

By no means all reservoirs are planned and exploited for multiple purposes, nor do they fully satisfy all demands. A significant share of the world's reservoirs is used primarily to produce hydroelectric power to the detriment of fishing, farming, flood control, etc.

Reservoirs should be used, first and foremost, for public water supply, irrigation farming, fishing, recreation, and flood control, since these requirements can be met only by reservoirs, while electricity can be generated by thermal stations. Reservoirs should occupy a minimum area, with dikes built to protect the most valuable land. Moreover, the biological productivity of reservoirs, through fish-breeding, should be higher than the biological productivity (crop yields, timber) of the territory before it was flooded. This can

partly compensate for the loss of land through flooding.

Research into ways of minimizing evaporation from reservoirs and lakes should be stepped up. Experiments are being conducted in spraying the water surface with hexadecanol, which forms a monomolecular film. When the entire surface is covered with film, evaporation is reduced by 90 per cent. However, wind and waves break the film, and further experimenting is required.

The world's thermal and hydropower stations now generate 3,300,000 million kilowatt-hours of electricity a year, of which the latter account for about 700,000 million. By the year 2000, as we have said, the output of thermal plants will reach 50,000,000 million kilowatt-hours annually. Hydropower stations will have an aggregate installed capacity of between 1,100 and 1,200 million kilowatt-hours and will produce approximately 8,000,000 million to 10,000,000 million kilowatt-hours. Less than three per cent of the world's hydropower potential is exploited today. We can see what vast development opportunities there are.

Water impounded by dams and streamflow regulated by reservoirs create highly favourable conditions for the further growth of navigation. Nearly half of the more than 140,000 kilometres of navigable waterways in the Soviet Union have depths that permit water transport to be expanded.

Navigation requires special water use only on rivers with locks. The amount used is not great. It averages 1.26 cubic kilometres a year on the Volga, and half of that, some 0.63 cubic kilometre on the Dnieper.[47] For all the rivers of the world the amount is probably no more than 20 to 25 cubic kilometres annually and applies to the lowest reservoir on a river.

In the Soviet Union, timber floating is practised on rivers with a total length of about 120,000 kilometres. This form of transportation has the drawback of clogging rivers when logs sink to the bottom. There is less danger of clogging when timber is floated in rafts.

FISHING

Pollution of rivers and lakes by factories, particularly oil refineries and chemical plants, and the construction of dams on rivers are detrimental to fishing. The lower reaches of the Volga and the North Caspian, where recent decades have seen a sharp decline in the catch of the more valuable migratory and semi-migratory fish, such as the sturgeon and pike perch, are an example. One reason is the drop in the level of the Caspian Sea due to natural causes and human factors. Another is irregular flooding of the Volga delta. The delta is not flooded every year because flood water accumulates in the reservoirs on the Volga and on the Kama, its tributary. In addition, the Volga-Kama chain of power dams prevents sturgeon from making their way upstream to spawn. This is detrimental to fish reproduction. Pollution of rivers and coastal waters by sewage and oil products has also harmed the fishing industry.

Can the contamination of rivers and lakes, so damaging to fish reproduction, be prevented? It certainly can. The world is now concerned with ways of improving the water in man's environment. Fish reproduction is one indication of the state of the environment. The Soviet Union now has a series of laws dealing with water conservation. Not long ago a decree was issued on measures to prevent pollution of the basins of the Volga and Ural rivers. Analogous measures are being adopted concerning other rivers.[48]

In the section on water supply we showed that the most effective ways of fighting pollution are to introduce recycling systems at industrial enterprises and use municipal sewage for irrigation and as industrial water. The aim should be to *prohibit the dumping of sewage into rivers.* Until we face up to this problem it will not be solved.

The wide use in recent years of chemical pest and weed killers, as well as of defoliants to remove leaves before harvesting, as in mechanized cotton picking, results in contamination of large areas of ploughland, forest and orchards; moreover, river meadows and lake shallows are sprayed with chemicals against the malarial mosquito.

Chemical weed and pest killers sprayed or sprinkled on the soil or plants are washed off during heavy rains and when the snow melts are carried by the surface runoff into rivers and lakes. The way to remedy the situation is by introducing tight restrictions on the amount of chemical weed and pest killers that may be applied. They should be used only when absolutely necessary. Large-scale research is needed into ways of preventing water pollution, which is becoming particularly dangerous with the rapid increase in the output of weed and pest killers.

Although no one proposes stopping the building of dams because they decrease the number of migratory fish, their construction should be accompanied by the building of fish hatcheries, the improvement of spawning grounds and other measures to help fisheries to adapt to the new conditions created by dams and reservoirs. This is now being done, but hatcheries should be built ahead of time, so that they are in operation before a dam is built. This is fully possible in a planned economy.

A water regimen that encourages spawning should

be maintained in the afterbays of dams. The case of lower Volga illustrates what can be done.

For spawning to take place the Volga delta should be flooded from about June 20 to July 20. To maintain the necessary water level the streamflow during these 30 days should be not less than 25,000 cubic metres per second. Only 12,000 cubic metres per second passes through the turbines of the Lenin Power Plant at Volgograd when it operates at full capacity. Therefore, 13,000 cubic metres per second has to be brought from reservoirs. Drawing such a large amount of water from storage lakes naturally hinders power production, but it is essential for the fishing industry.

To reduce discharge that is unproductive to the power industry, a take-down dam is being built at the head of the delta that will, during the spawning period, distribute 8,000 cubic metres per second through the Buzan channel into the eastern section of the delta for normal spawning conditions, and 4,000 cubic metres per second into the western section to maintain navigable depths on the Bakhtemir channel. Normal spawning conditions in one half of the delta should, it is believed, ensure fish reproduction. This large-scale experiment is an example of a multipurpose approach to the problem.

But this, we feel, is not enough. Ways must be found of enabling fish to spawn throughout the delta, with the Volga flow regulated by dams, since we do not know whether half the delta would ensure fish reproduction on the desired scale. We suggest building in the Volga delta a system of underwater barriers and, on the big channels, locks as well. This would slow down the streamflow in the delta, yet would not prevent the passage of fish. In the semi-blocked sections, with water discharge reduced by half, there would be

enough area and sufficient depth for fish to spawn and grow.

Now we have to determine whether it is necessary to plan the special use of water from reservoirs for hatcheries and the fishing industry. A certain amount is necessary for fish needs, for pond fish-breeding and to replace reservoir evaporation losses. We took the latter into account in the previous section. As for the first two applications, they cannot be appreciable in absolute magnitudes.

According to rough estimates, the total world irretrievable water use for fish-breeding and angling comes to about 15 cubic kilometres a year. In future this will rise to between 75 and 100 cubic kilometres.

RECREATIONAL USES

Rivers, lakes and reservoirs attract many holiday-makers. Boat trips on the Volga and Kama rivers and the Volga-Don and Volga-Baltic canals are popular. So are camping trips by sailboat or canoe. In future, rivers, lakes and reservoirs will be used even more as recreation areas. The benefits of this important use of water resources are self-evident.

We must consider the demands recreational uses make on water resources and the amount of water needed. Recreation areas will have to be extended, national parks established, and places set aside for anglers. Such zones should be sited far from industrial centres, in places where rivers and lakes are still unpolluted.

In general, the problem of maintaining pure water in rivers, lakes and reservoirs will be basically solved when the main principles of using and conserving water resources that we have proposed are followed. The principle of not pumping sewage into rivers and reservoirs must be followed with particular care in recrea-

tion zones. So must restrictions in the use of weed and pest killers in agriculture and forestry.

A certain amount of water in rivers and lakes has to be set aside for recreational purposes. Artificial lakes are built especially for this in regions without natural bodies of water. At these lakes, as at most drainage lakes, fluctuations in water level should be minimal. Therefore, reserves must be built up for the purpose.

Methods of planning water resources for recreation and tourism have not yet been worked out. In seeking a solution to this problem we proceed from the following considerations:

1. Streams, lakes and reservoirs in recreation areas should be especially protected against contamination. This refers to land resources as well; no large-scale sewage irrigation should be planned within recreation areas.

2. Water intake from streams, lakes and reservoirs in recreation zones should be regulated with a view to reducing natural fluctuations in water levels.

3. Timber felling in recreation areas should be allowed only when aimed at maintaining and improving the water-conservation properties of the forestland.

Another point directly related to the water problem is the moral aspect, that is, the duty of every adult and adolescent to obey the rules and regulations concerning the conservation of water, vegetation and wildlife. Although much has been written about this moral obligation in newspapers, magazines and books no noticeable improvement has yet taken place. It is generally thought to be the duty of teachers of geography and natural science to instil a love of nature in children. Such an attitude is wrong. Every teacher should love and understand nature, and train the children in his classes to do the same. The fundamen-

tals of nature conservation should be included in the curriculums of universities, teacher-training schools and colleges, and, especially, secondary schools. Children should be taught from their earliest years to love nature and feel a sense of responsibility for the environment and its conservation. Such an attitude should be a part of pre-school education and, particularly, education in the home.

Organizations which exploit natural resources—the soil, the forests and waters—should show an equal concern about the environment. The soil should be correctly cultivated; no more timber should be felled than can be replaced by natural growth; forest soil should be protected from damage during timber felling. These and many other questions are directly related to water conservation.

THE KEY TO CLEAN WATER

If water is polluted, it is of little use, no matter how much of it there may be. The highest standards are set for drinking water, and water for fish-breeding and for the food, pulp and paper, and certain other industries.

In recent decades the quality of the water in rivers, lakes and reservoirs has sharply deteriorated because municipal and industrial wastes are dumped into them.

A brief review of the consequences of discharging wastes, treated or untreated, into bodies of water will help us to ascertain the key conservation principle.

One cubic metre of untreated sewage spoils between 40 and 60 cubic metres of naturally pure water. That is the maximum ratio to which river water can be contaminated and still be used again, although not without reservations. But on a number of rivers, even large

rivers, in industrial areas, the ratio between sewage and water discharge, particularly in the low-water season, is so unfavourable that a river's powers of self-cleansing are incapable of coping with the situation.

The standard of river and lake water in some areas deteriorated to such an extent that it could no longer be used for water supply, and the question of waste treatment arose. But equipment that will clean water properly is extremely complicated and costly. Furthermore, treatment is not effective enough to be considered the main method of conserving water in future. Even the most up-to-date treatment methods do not clean water completely. Cleansing by 80 to 90 per cent is considered good. It has proved impossible to eliminate from 10 to 20 per cent of pollutants which are the most stable. Hence, "purified" waste water also pollutes rivers and lakes, although to a lesser degree.

For purified sewage to become suitable for use in the process of natural self-cleaning it has to be diluted by six to fourteen times as much pure natural water. As we see, waste treatment plants produce a definite effect, reducing the ratio of natural water required for dilution by 80 to 85 per cent. But with water consumption steadily growing, the prospect is not particularly hopeful even if all waste water were to be treated.

The volume of sewage is expected to increase fivefold in the Soviet Union within the next 15 to 20 years, and more than 16-fold in the whole world during the next 30 years (Table 21, p. 143). The treatment of all waste water would cost thousands of millions of roubles in capital outlays and running expenses. Even if this were done there would still be no reduction as a whole in the contamination of rivers; treatment would diminish pollution content by 80 to 85 per cent, as

noted above, but the total volume of waste waters would increase from five- to 15-fold. Therefore, if all sewage were treated and discharged into rivers the general pollution level would remain the same in the coming decades, or would drop insignificantly, despite the vast expenditures.

Treatment techniques will improve, of course, but the possibilities are limited by the economic factor. In the final analysis, the methods of distillation or regeneration could be employed to achieve 100 per cent cleansing but this would call for still larger expenditures. While technically possible, these methods of dealing with sewage would be too expensive and consume too much electricity.

Improved treatment methods will not alter the overall picture. They can only affect the length of time in which the general volume of post-treatment pollution remains unchanged.

From Table 21 we can see that disaster awaits us if we plan to continue pumping sewage into streams, even if treatment methods become much more refined. By the year 2000 all river water will have been used up in diluting waste water. All streams will have turned into sewage drains.

Polluted rivers contaminate the seas. Ultimately, the inland seas and the coastal areas of seas and oceans would become polluted.

Waste treatment does not solve the problem, but it is an auxiliary method. The main goal, as we have said, is a system of measures aimed at *minimizing, and in a number of cases completely eliminating, the discharge of waste waters into streams, lakes and reservoirs.* This is the only radical way of solving the problem since it does away with the need to use a vast amount of river water to dilute sewage. By ceasing

to pump sewage into waterways we will make all river water suitable for use. The volume of pure water resources will increase at least several times over.

Use of municipal sewage for irrigation, except for the water suitable for industrial use after treatment, which amounts to about 450 cubic kilometres a year, is very effective since this type of waste water contains a large amount of organic fertilizer. On the other hand, the soil is the best agent for making municipal sewage harmless. When applied in moderation this method solves the problem, for then waste water is not returned to streams and lakes.

The hygienic, agronomic, technical and economic aspects of the use of municipal waste waters for irrigating farm fields have been tested in the Soviet Union and other countries. When irrigation systems are built correctly and flooding is carefully regulated, the outlays involved in building a system will be recouped within three or four years through the bumper harvests of fodder crops.

Industrial plants, including thermal power stations, must build recycling installations. A plant starts off with the volume of water needed for a cycle, and the amount lost in the production process (usually from 10 to 15 per cent of the total used) is replaced regularly from the supply source.

Closed-cycle operation has a number of advantages. First, it stops the discharge of industrial effluents into the waterways. Second, the plant can treat its wastes more cheaply and thoroughly than municipal sewage, which contains a large number of diverse pollutants. Besides, it can modify its production process to prevent unnecessary pollution of the water it uses. The plant will be encouraged to save water since each extra cubic metre of waste water pumped into the plant's sewage system calls for extra expenditure to

cleanse it. Valuable by-products will be extracted from the wastes during treatment.

Water so polluted that it cannot be recycled, such as the effluent discharged from some chemical plants, should be destroyed, or distilled and regenerated.

Raising the level of a river in a low-water period by regulating reservoir discharge and through land and forest improvement is an important element of a water conservation scheme. Another is the creation of groundwater reservoirs by storing up surface water, primarily flood water. This will create stable supply sources and also improve the quality of the water since underground water that does not lie too near the surface is more reliably protected against pollution.

As we see, there is no universal way of preventing deterioration in the quality of water. The main measure—an end to the dumping of waste waters into streams, must be combined with a wide range of supplementary steps. *Conservation in the process of use* should be a common feature of all these measures.

THE ESSENCE OF THE MULTIPURPOSE APPROACH

The multipurpose approach in planning water use and conservation and in designing municipal and industrial water projects is now generally accepted. Often, however, only lip service is paid to it. Even though all the features and types of water resources, as well as the interests of all branches of the economy, may have been taken into account, the absence of overall, unifying principles and integrated co-ordination between individual problems often makes the plan or project a jumble. On the face of it, the approach is multipurpose but actually this is not the case. Hydropower is still often given priority, relegating agriculture, fishing and navigation to the background.

A multipurpose project is more than the simple sum of all the problems and measures connected with one branch of the water-management industry and related industries. It is a project in which complex problems and measures are organically interconnected and united by common ideas and goals.

What are labelled multipurpose projects often fail to co-ordinate the use of river water, groundwater and soil moisture—as though these water sources existed in nature independently of one another.

Some aspects of the multipurpose approach were examined in the first three chapters of this book. Unity of water resources is the basic theoretical principle. All parts of the hydrosphere and the various sources of water are closely interconnected in that magnificent process, the hydrologic cycle.

On the other hand, the connections between water and the other components of nature are so important and their consequences so great that they deserve the closest attention in practice. Only then can a project to use and conserve water resources be really considered to have multiple purposes.

A great deal still has to be done, including the training of experts in this field, before the multipurpose principle can be really put into practice. The multipurpose approach is extremely involved; the most serious attention should be given to its development and practical application.

It is easy to meet the needs of the population and all branches of the economy in regions that are rich in water resources in relation to the demand. But where water is insufficient, priorities have to be established, or else the resources may be expended on non-essential needs, leaving important requirements unsatisfied.

Natural and economic priorities may change, but they should evidently be based on the following pat-

tern: (1) drinking water; (2) food industry; (3) domestic needs; (4) recreation; (5) livestock raising; (6) fish-breeding; (7) irrigation and non-irrigation farming; (8) industry and heat-and-power plants; (9) hydropower stations; (10) navigation.

Human needs come first in the above list, while the power industry and navigation come last because they can be replaced by other sources of energy and modes of transport.

Priorities cannot, of course, be established once and for all. In some cases, water for the mining or other industries might have to be given priority.

The multipurpose approach calls for efficient siting of industries. But water should not add substantially to production costs under any circumstances. In a number of cases it may be more profitable to transport raw materials and finished goods than to transport water. The economic aspect plays a big role in planning the use of water resources.

Water management economic indicators and criteria have been worked out insufficiently or lop-sidedly. The generation of cheap electricity, for example, places a burden on agriculture (valuable land is flooded), fishing (fish are prevented from migrating, and spawning is interfered with) and even on navigation (ships of a heavier type have to be used on big reservoirs).

HYDROECONOMIC PROBLEMS

The economic aspect of water use and conservation is a big problem in its own right that has been little studied. And it is becoming more important than ever with the increased use of water resources and the growing disproportion between demand and supply.

The cost of water and the provision of economic incentives to save water and prevent its pollution are

now being discussed more and more often. From the standpoint of its use, water, like many other natural resources, is a raw material. This is obvious, but the practical conclusions are not simple because we are accustomed to regarding water, like air, as an inexhaustible gift of nature. From this it follows psychologically that water may be taken from any source in any quantity, that it may be contaminated at will and that sewage may be dumped anywhere.

There are rules and regulations and inspection agencies, of course, but even the most detailed regulations cannot cover every eventuality. Definite *principle* must be established and strictly observed, not the least of them being the provision of economic incentives.

Every wrong step taken in handling water resources a step which at first glance might seem to be economically justified for the given situation, results in sizable losses after some time. "Let us not, however, flatter ourselves overmuch at our human conquests over nature," Engels warned us. "For each such conquest takes its revenge on us. Each of them, it is true, has in the first place the consequences on which we counted, but in the second and third places it has quite different, unforeseen effects which only too often cancel out the first."[49]

If we were to count all the ways in which nature has revenged herself on man it would add up to vast material losses; these can most clearly be seen from what it costs to eliminate the consequences.

We believe that water intake from sources should be paid for. Rates of payment could differ depending on the use to which the water is put. Water for drinking and other domestic uses should be free of charge, but water for industry, heat power generation and other production purposes should be paid for.

It would be still more rational to set a fee not so much on water intake as on the discharge of waste waters into streams, lakes, reservoirs and the sea. Rates would depend on the degree to which the sewage is contaminated. As pollution is reduced the cost of discharging waste water would drop in geometrical progression. This would, first, reduce the volume of waste water discharged and, consequently, the amount of water taken from sources; second, encourage industrial plants to recycle their water; third, encourage consumers to reduce to a minimum the contamination of the water they use.

Double payment, for water intake and for the discharge of waste water—during a transition period, until waste water is no longer pumped into streams and reservoirs—could be in the nature of rent. The money could be used to promote more efficient use and conservation of water resources.

The above, of course, is a general pattern that would have to be worked out in greater detail.

Another economic criterion is the output of goods per unit of water. This is extremely important in farming, particularly irrigation farming. It also holds true for industrial water. This criterion would encourage the saving of water.

In a capitalist economy the efficiency of water use is measured in terms of money. According to data for the western states of the USA, one acre-foot (1,233.5 cubic metres) of water used for municipal water supply accounts for 3,000 dollars' worth of gross product. In recreation areas the same amount of water accounts for 200 to 300 dollars' worth of gross product, and in agriculture only for 40 to 50 dollars' worth.

One should not, of course, conclude from these interesting figures that water should not be used in

irrigation farming, where it yields a gross product of less value than in other branches of the economy. In terms of the future, however, when there will be more areas with a water shortage, and water use priorities will have to be established, irrigation farming will by no means come at the top of the list everywhere.

The Soviet Union gives priority in the use of water for irrigation to Central Asia and Transcaucasia, which have the country's warmest climate and can grow subtropical industrial crops, for instance, cotton. The trend, however, is for industrial crops to be replaced by synthetic materials.

It should be remembered, besides, that the road to more efficient use of water in farming lies through increasing the yields per hectare and reducing production costs. Irrigation farming—at any rate until watering is completely mechanized—in many cases involves greater labour and water expenditure per unit of produce than non-irrigation farming.

Sewage irrigation changes the economic pattern of irrigated agriculture because it substantially increases productivity and also because the soil is the most effective sewage cleansing agent.

It should also be recalled that the capital outlays needed to build irrigation systems using waste waters for intensive meat and dairy suburban farming are recouped in three or four years just from the sale of the produce, not counting the highly effective cleansing of sewage.

The economic aspects of water use and conservation pose many involved problems that have as yet hardly been studied. The brief considerations put forward here touch on only a few of the fundamental points.

* * *

This chapter has surveyed a wide range of complex problems connected with water use and conservation. Our aim has been to show the importance of establishing definite, thoroughly substantiated principles on which development of the water economy should rest. In doing so, we must foresee the future results of steps taken today.

Prognostication will help to find correct solutions to the problems of using and conserving water resources. Long-range forecasting has enabled us to establish a number of principles of water planning, use and conservation. These principles will determine technological policy in the development of the water economy.

It was assumed in planning the long-term use and conservation of water in the United States that for the predicted period "there will be no substantial changes in governmental policy that might influence the use of water resources in future."[1]

Our survey of the economic component of the hydrologic cycle and approximate forecast show that water use and conservation principles will have to be changed substantially. Only this can prevent water resources from being exhausted and assure a permanent supply. Supplies must be increased by changing the hydrologic cycle through extended reproduction of water resources, a problem to which we devote the next chapter.

CHAPTER FIVE

Controlling the Hydrologic Cycle

POSSIBLE TRENDS

The changes in the hydroeconomic component of the water cycle discussed in the preceding chapter are an important part of the steps which must be taken to prevent the depletion of man's water resources. But these steps alone are not sufficient. To ensure a *permanent* supply of water man must reshape the hydrologic cycle.

It hardly seems possible, at first glance, that he could influence the vast hydrologic cycle in any appreciable way. Actually, though, a number of elements of the cycle can be controlled and changed.

The water in the ocean and in the air is the hardest to influence. Control of ocean currents is still beyond man's powers, but in time he will learn how to change them in such a way as to improve the climate of large land areas. It is hard, though, to foresee all the possible consequences. P. M. Borisov has proposed an interesting scheme to eliminate the ice of the Arctic Ocean and warm the Arctic basin by intensifying the northern branch of the Gulf Stream.[50] But it is feared this might reduce precipitation in the temperate

zone of Eurasia, which does not have enough moisture as it is. Science cannot yet tackle such problems with confidence.

Changing the climate by acting directly on atmospheric processes, on air circulation, on the movement of atmospheric moisture, is also a problem for the future. Only a slight local influence can be exerted on the atmosphere at present. It would take an enormous amount of energy to act on the atmosphere on a scale that would substantially affect the hydrologic cycle or lead to climatic changes that would influence water resources and promote their replenishment. In future, ways will undoubtedly be found to control the hydrologic cycle by acting on the atmosphere.

Measures are now being taken on an extensive scale to influence moisture exchange in the layer of air just above the earth. Systems of shelter belts, for example, alter the character of the terrain, making it less smooth. This changes the movement of the air several hundred metres above the trees and increases the probability of vapour condensation and precipitation.

The surface and soil chords of the hydrologic cycle can be changed substantially by acting on the topsoil and vegetation. The most ancient method is irrigation. Irrigation modifies the local water balance and enables crops to be grown in desert and semi-desert areas where farming is impossible under natural conditions. Non-irrigation farming, drainage, and the felling and planting of forests often bring about far-reaching changes in the local hydrologic cycle and regulate the local water balance.

Reducing evaporation from ploughland to increase transpiration helps to produce larger harvests in drought-afflicted areas.

Man's ability to change the groundwater arc of

the hydrologic cycle is still limited. In future, he will store groundwater in increasingly large quantities, and eventually only this source will be used for drinking and domestic needs. That is because surface waters—streams and lakes—are becoming more and more contaminated by municipal and industrial sewage, and it is very difficult to cleanse them completely.

It would be proper here to consider a methodological point that influences the approach to changing the water balance of a territory, particularly the water content of rivers. In the first half of the last century some experts suggested, in view of the drop in the level of some rivers in Europe due to forest felling and more intensive farming, that man could change the regimen of rivers only by changing the climate. This gave rise to the view that climate was practically the only hydrological factor. But at the end of the century the Russian soil scientists Voeikov and Dokuchaev showed that the climate did not have to be changed to bring about hydrological changes, that by acting on soil and vegetation it is possible to increase the water content of rivers.[51,52]

Important and convincing though this new theory was, the old climatological concept was exhumed from the archives of science and still has some supporters today. For one thing, they claim that while by acting on the soil man can change the regimen of small streams and small areas, he can bring about hydrological changes on large rivers and over extensive areas only by changing the climate. In recent decades, however, the theory that action on the soil can lead to hydrological changes has acquired many more adherents. Publication of the results of a large number of experiments has reinforced this theory. We present some of the results below. It is a fact that

widespread action on the soil changes the water balance of large areas and the water regimen and water content of large rivers.

"Divide and rule" was the epigraph which Voeikov chose for an essay where he argued that while it is hard for man to change nature as a whole he can change separate parts of it. The idea of "divide and rule" in the transformation of nature still holds true to a certain extent today. But the world has undergone such big social and technological changes in the past fifty years that it is now possible to remake nature and parts of the hydrologic cycle on a large scale. The chains of reservoirs that have been built on the Volga, Kama, Dnieper, Angara, Colorado, Missouri and many other rivers, the large navigation and irrigation canals, and the plan to divert water from northern rivers into the Kama and Volga are just a few examples.

Man's influence on plant life and the soil, along with the building of large-scale hydraulic works, changes the regimen of rivers and, consequently, the surface chord of the hydrologic cycle. Cultivation improves soil permeability. This alters the water balance of large areas and the regimen of the streams flowing through them.

Now let us examine changes in the hydrologic cycle in greater detail.

RESHAPING THE LOCAL WATER BALANCE

Water resources can be regulated not only by reservoirs but also by soil improvement. This influences a region's hydrologic processes in their initial stage, before water is collected as streamflow or groundwater. When practised on a massive scale, it can alter and regulate the water balance over large areas, including big rivers.

The bulk of the Soviet Union's grain is grown in forest-steppe and steppe regions, which periodically suffer from drought. Insufficient soil moisture is the main cause of crop failures.

One way of coping with the problem is, of course, irrigation, and the irrigated area is now being extended for grain as well as for cotton and other industrial crops. To increase the country's grain output, however, the non-irrigated grain area, which in future will continue to be many times larger than the irrigated area, must also be made to produce higher yields per hectare.

This is being done by regulating soil moisture resources in the drought-afflicted regions. Before collective farms were set up, autumn ploughing was not, as a rule, practised in the steppe and forest-steppe zones. Since the peasants did not have common pastures they put their cattle into the fields to graze on stubble after the grain was harvested. As a result, soil permeability deteriorated.

The primitive implements used by the peasants in those days—the horse-drawn plough, which turned up the soil to a depth of not more than 16 centimetres, and the wooden plough, which turned up 10 to 12 centimetres of soil—did little to improve matters.

When the snow melted in spring, water streamed off the fields. On sloping terrain the intensive runoff led to heavy erosion. Valuable topsoil was washed away; gullies formed.

Lenin's Decree on Land, in November 1917, laid the foundation for an improvement in farming methods. The use of tractors to cultivate the soil marked a big step forward. Autumn ploughing on a large scale began in the early thirties. Today it is practised over the bulk of the area under spring crops.

Autumn ploughing has substantially modified the

water balance of arable land. It has made the topsoil much more friable to a considerable depth, and therefore more permeable during snowmelt. Soil moisture resources have thus increased and surface runoff from the fields has been reduced. At flood time less snowmelt flows into steams, thanks to which the volume of floodwater in many rivers is diminished. More favourable conditions have been created for replenishing groundwater, which feeds rivers in drought periods, when water is at a premium.

The magnitude of the changes following from this important trend is calculated through field experiments that compare the water balance of uncultivated land with that of ploughland cultivated in different ways.

The findings of a study of spring runoff conducted at a Kursk Region experimenal station of the Geography Institute of the USSR Academy of Sciences are a case in point (Table 22).

TABLE 22

SPRING SURFACE RUNOFF AND INFILTRATION

Land and methods of cultivation	Snow and precipitation, P, mm	Surface runoff, S, mm	Infiltration, $W=P-S$, mm	Runoff coefficient, $\frac{S}{P}$
Ploughland				
stubble	88	64	24	0.73
winter crop	102	80	22	0.80
autumn-ploughed	73	24	49	0.33
Uncultivated land				
pasture land	87	45	42	0.52
virgin land	133	23	110	0.17
forest	160	0.0	160	0.0

We have put pasture land into the category of virgin land, although this is not entirely correct since it is trampled by cattle and grazed, which disrupts the natural soil-formation process, making the soil less permeable and increasing surface runoff by at least three times compared with virgin land proper. Surface runoff is even greater from stubble, which is now rarely found in fields in spring and even more rarely in fields planted to winter crops. Runoff is least of all from autumn-ploughed land. In the forest-steppe zone the soil in forests that has not been disturbed by grazing is so highly permeable that numerous observations over a long period of time have not revealed any runoff at all.

The relatively little runoff from virgin land (half as much as from ploughland) is due to the highly structured soil and the thick layer of dead grass. On virgin land, dead plants do not have time to decay, and the soil becomes covered with a layer of vegetal matter that increases permeability.

A fairly large amount of data has appeared in the past 15 or 20 years showing how much the soil cover influences the hydrologic cycle and the water balance. The facts disprove the view that the climate, or precipitation, is practically the only hydrological factor. Of course, it plays a significant role, but it is only one of the many factors influencing the water balance. Other factors, particularly soil cover, as we see, are also important.

As has been demostrated both in theory and experimentally in the past few years, the soil cover factor is of considerable importance; it will help to find solutions to a number of major practical problems.

Experimental data obtained at 18 stations are summarized in Fig. 7.

The curve of Fig. 7 shows the degree to which autumn

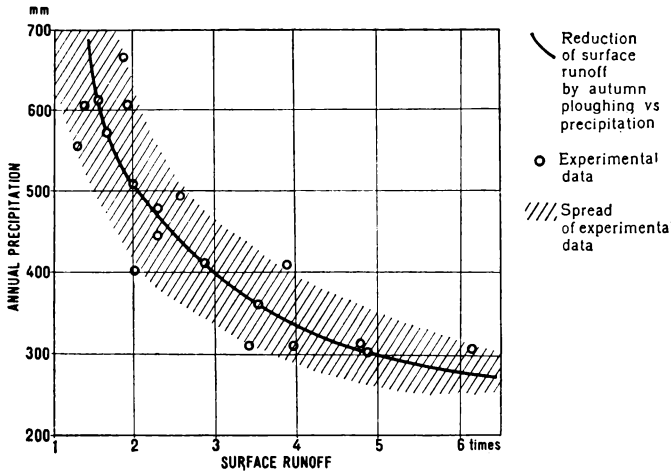


Fig. 7. Pattern of reduction of autumn ploughing, based in runoff under the influence on experimental data

ploughing reduces overland runoff (horizontal axis) as a function of precipitation (vertical axis). The curve can be used to assess the hydrological effectiveness of autumn ploughing in any region. For example, with 400 millimetres of annual precipitation the surface runoff from autumn-ploughed land is three times less than from stubble or long-fallow land; in regions with 300 millimetres of precipitation it is five times less. Autumn ploughing reduces overland runoff 3-6 times in the steppe zone, 1.5-3 times in the forest-steppe zone, and 1.3-2 times in the forest zone.

Deep tractor ploughing (22 to 27 centimetres) makes the topsoil much more permeable. Mineral and organic fertilizers, which promote plant growth and the

development of a good root system, also contribute to better absorption of water by the soil.

Deep autumn ploughing in the steppe and forest-steppe zones of the European part of the Soviet Union has increased annual soil moisture by approximately 15 cubic kilometres since World War II. While this is a substantial contribution to higher farm productivity, it is only a fraction of the additional reserves of water we would have if water losses were reduced.

Not more than 40 per cent of the water available to ploughland goes into plant transpiration at present. Approximately 60 per cent, or some 220 cubic kilometres, equal to the annual discharge of the Volga, is lost to agriculture. This 60 per cent is a reserve from which productive use of water could be increased.

The figures in Table 23, based on experimental

TABLE 23

WATER RESOURCES OF PLOUGHLAND IN ZONES OF INSUFFICIENT AND VARIABLE MOISTENING IN THE SOVIET UNION (BETWEEN BEGINNING OF SPRING SNOWMELT AND HARVEST PERIOD)

	Total resources	Soil moisture resources	Transpiration	Losses			Total loss
				surface runoff	snow blown off	evaporation	
At present							
in cubic kilometres	364	290	145	58	16	145	219
in percentages	100	80	40	16	4	40	60
In future after improvement							
in cubic kilometres	364	335	225	21	8	110	139
in percentages	100	92	62	6	2	30	38

data, show that further improvement of cultivation methods (deeper ploughing, contour ploughing, ridging, etc.) and the use of fertilizer to make the soil more permeable, can reduce overland runoff and consequently increase soil moisture by about 38 cubic kilometres.

At least eight cubic kilometres can be added to this by reducing the amount of snow blown off the fields into ravines and gullies. Shelter belts effectively retain snow. All told, with the application of other methods, this source of losses could be cut in half.

The use of shelter belts to control evaporation is being studied experimentally. Shelter belts change the regime of air turbulence close to the ground and lessen wind velocity, thereby reducing the evapotranspiration rate on the fields between the belts, and leaving more soil moisture for use by the plants. All this contributes to bigger harvests.

Studies carried out on wheat fields in the Kamennaya Steppe have shown that windbreaks increase transpiration by 15 per cent, that is, to 63 per cent of total evapotranspiration, as against 48 per cent in the open steppe. The wheat yield is doubled. The transpiration coefficient on a field protected by a shelter belt drops to 350, from 450 in the open steppe. This means that each ton of crop vegetation uses 30 per cent less water than in the open steppe. While not increasing the amount of soil moisture as a whole, shelter belts help cultivated plants to use water more fully and effectively, as a result of which they are better provided with water than in unprotected fields.

Experiments on irrigated wheat land east of the lower Volga produced similar results. Windbreaks increased transpiration by 13 per cent and yields by 30 per cent. One ton of plant matter on a field situated between shelter belts used 265 cubic metres

of water, 16 per cent less than the 320 cubic metres consumed in the open steppe.

There are methods, not yet fully tested, of mulching crops with chemical substances, among them oil products, to protect the topsoil and reduce evaporation. Experiments in the United States have established that mulching increases grain yields by 50 to 100 per cent, beet yields by 16 per cent, and the yields of several other crops by 34 to 58 per cent.

Naturally, windbreaks provide benefits when they are combined with correct tillage of the soil, timely planting, the use of high-yielding strains of seed, and the like.

Shelter belts help to regulate soil moisture and raise yields only when they are correctly sited. The main part of a belt should be planted across the incline of the terrain. It should form a square protecting a field of from 40 to 60 hectares in area. Furthermore, it should let some air and wind pass through, otherwise it will influence only a small area.

For the most part, the planting of trees at the mouth or along the shoulders of ravines and gullies does not help to halt erosion. The way to control erosion is by reducing the surface runoff. This can be done by planting forest belts and improving soil permeability within the drainage basin of the ravine.

A method of designing windbreaks that enables their effect to be precalculated has been developed in the Soviet Union.[9]

Estimates based on theoretical research and a large number of experiments show that the planting of shelter belts in the steppe and forest-steppe regions of the Soviet Union can, when combined with scientific farming methods, provide agriculture with an additional 80 cubic kilometres of water annually. This amount of water will increase the grain harvest

from an area of 100 million hectares by about 40 to 50 million metric tons. The retention of from 35 to 40 cubic kilometres lost from the fields in surface runoff can boost the harvest by 15 to 20 million tons.

These examples illustrate the results that can be obtained by regulating soil moisture. A more favourable water balance on ploughland contributes to higher yields. This kind of all-round approach to the water problem is linked up with the problem of providing a growing population with food.

FORESTS AND THE WATER BALANCE

Forests greatly influence the water balance. Since productive forests have a high transpiration capacity, the moisture thus given off by forestland often exceeds the evaporation losses from a similar area that is not wooded. This property of forests has often been viewed as a negative feature, and there have been proposals that forests should be cut down to increase streamflow. Discussion of the hydrological role of forests went on for decades, and it ended in favour of forests. The water regulation properties of forests are now generally recognized to be beneficial. A law protecting forests as a water conservation factor has been in force in the Soviet Union since 1936.

The debate arose chiefly out of the failure to realize that transpiration is not waste since it helps to produce timber and farm crops. As we have said, it is one of the most effective forms of water use.

Is there any benefit from a low level of transpiration if as a result a forest's productivity is low? Certainly it is better if a forest is highly productive, even though more moisture is given off in the form of transpiration. Furthermore, in this case water efficiency, that is, the amount of water used to produce

TABLE 24

ANNUAL WATER BALANCE OF FORESTS AND GRASSLAND

Balance items	Fir forest 90-100 yrs old, cover factor — 0.8 *		Grassland	
	in mm	% of precipitation	in mm	% of precipitation
Precipitation (P)	565	100	565	100
Surface runoff (S)	17	3	215	38
Subsurface runoff (U')	119	21	0	0
Groundwater runoff (U)	119	21	102	18
Total runoff ($R = S + U' + U$)	255	45	317	56
Transpiration (T)	158	28	90	16
Soil evaporation (N)	28	5	158	28
Evaporation of precipitation from crown cover of forest (E')	124	22	—	—
Total evapotranspiration ($E = T + N + E'$)	310	55	248	44
Total moistening of soil ($W = P - S$)	548**	97	350	44
Groundwater recharge coefficient $\left(K_u = \frac{U}{W}\right)$	0.43***	—	0.29	—

* Cover factor 0.8 means that 80 per cent of the forest area is covered by tree crowns.

** 424 mm if transpiration from forest crown area is not counted.

*** Including subsurface runoff.

a unit of plant matter, is higher than in an unproductive forest. Here we have a complete analogy with the water balance on productive and unproductive fields.

Forest land is important hydrologically because of its water-regulating action. Thanks to the high permeability of forest soils, at least two or three times greater than that of field soils, snowmelt and rainwater are easily absorbed. Table 24, compiled from experimental data, illustrates this.

There is practically no surface runoff in forests; it does not exceed three per cent of annual precipitation. In meadows it amounts to as much as 38 per cent. Subsurface and underground water runoffs in a forest equal 42 per cent of the precipitation, as against only 18 per cent in a field. This is the main hydrologic action of forests, which intensify the lithogenous arc of the hydrologic cycle. Stable groundwater flow is therefore greater in rivers with forest watersheds.

The total water-regulating action of the Soviet Union's forests is approximately equivalent to that of reservoirs with an available storage of some 200 cubic kilometres a year. From this we can see the hydrological benefits of forests, irrespective of the amount of water that goes on transpiration.

Now let us assess the possibilities of maintaining or even increasing the water-regulating action of forests while exploiting them. Theory, experiments and practice show that timber felling, if it does not exceed the natural growth and if a number of other rules are followed, will not impair the regulatory action. It is extremely important to retain the high permeability of forest soil. Unfortunately, this point is often ignored.

The heavy skid tractors now widely used to haul logs from felling areas to the nearest road do particular damage to forest soils.

Log transportation by ropeway, a method now being tested, does far less damage to the soil. So does horse-drawn skidding, especially in winter. The use of helicopters seems promising.

During logging it is extremely important to prevent topsoil damage, which impairs water-regulating action. While it takes from eight to twelve years to renew a felled area to the point where the tops of the trees meet, it takes decades to restore the permeability of the forest floor. When correctly carried out, felling will not impair soil permeability but, on the contrary, will contribute to the planting of more highly productive trees to replace those felled and thereby helps to improve water regulation.

Forest conservation means water conservation. It is therefore doubly important to conserve forests and make them more productive.

Much attention will undoubtedly be paid in future to improving the water-conservation properties of forests, in particular, through higher forest productivity, and with a possible increase in transpiration.

CHANGING THE REGIMEN OF RIVERS

The regimen of a river can be imporved in two fundamentally different ways. One is through engineering projects to regulate river flow. The other is by agricultural and land improvement measures in the watershed. Both methods make streamflow more even, reducing the amount of flood flow and increasing flow in low-water periods. In both cases, overall annual streamflow is reduced.

The chain of reservoirs on the Volga and Kama rivers has an available storage of about 90 cubic kilometres. By correct manoeuvring of their storage the reservoirs can be made to accumulate about half of

the volume of spring flood flow. This water is then used to generate electricity in low-water periods, and at the same time it doubles and trebles low-water streamflow. The stabilization of the streamflow to such an extent is a major hydroengineering achievement in reshaping the Volga's water regimen.

Such changes in river regimens, as well as intake from rivers for water supply, irrigation and other hydrotechnical purposes, are usually quite noticeable and hence are as a rule taken into consideration in water-management planning. But ordinarily changes in flow connected with agriculture, even on an appreciable scale, go practically unnoticed unless special methods are used to register them. Their assessment is complicated by the fact that they usually amount to less than the coincident natural fluctuations in streamflow and are disguised by the latter.

Yet in the arid zone an increase in soil moisture is usually achieved, as we have pointed out, by retarding the overland runoff that feeds rivers. The more runoff retarded and the greater the share transferred to the soil, the less the amount of water that reaches the rivers.

A knowledge of a territory's future water budget and river regimen is important in planning water use and conservation. In a number of cases, particularly in arid zones, the use of water for farming will reduce the amount available in future. Hence, a forecast cannot be based only on the average data over many years.

If estimates of water resources are not to be exaggerated they must be based on a forecast of the water balance. A long-range forecast based on a study of the Soviet Union's rivers over the course of many years has been drawn up by the Institute of Geography of the USSR Academy of Sciences (Table 25 and Fig. 8).

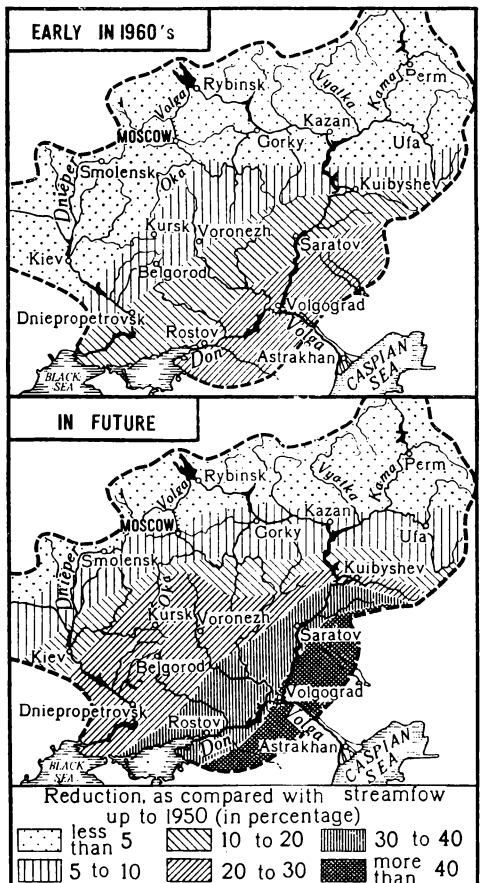


Fig. 8. Changes in streamflow under the influence of agriculture

TABLE 25

PAST, PRESENT AND PREDICTED WATER BALANCE OF THE DNIEPER, DON AND VOLGA RIVERS (CUBIC KILOMETRES)

	Precipitation, *P*	Total streamflow, *R*	Surface runoff, *S*	Groundwater flow, *U*	Total moistening of territory, *W*	Evaporation, *E*
Dnieper						
Past (normal until 1950)	260	50.7	34.3	16.4	225.7	209.3
Present	260	49.2	32.7	16.5	227.3	210.8
Long-term forecast	260	45.9	29.0	16.9	231.0	214.1
Difference:						
present-day changes	0	−1.5	−1.6	+0.1	+1.6	+1.5
expected changes	0	−4.8	−5.3	+0.5	+5.3	+4.8
Don						
Past (normal until 1950)	167	29.5	22.7	6.8	144.3	137.5
Present	167	25.7	18.5	7.2	148.5	141.3
Long-term forecast	170	21.2	13.6	7.6	156.4	148.8
Difference:						
present-day changes	0	−3.8	−4.2	+0.4	+4.2	+3.8
expected changes	+3	−8.3	−9.1	+0.8	+12.1	+11.3
Volga						
Past (normal until 1950)	706	260	186	74	520	446
Present flow	706	254.5	179.7	74.8	526.3	451.5
Long-term forecast	706	241.6	164.6	77	541.4	464.4
Difference:						
present-day changes	0	−5.5	−6.3	+0.8	+6.3	+5.5
expected changes	0	−18.4	−21.4	+3.0	+21.6	+18.6

The estimates were made according to a water balance method[9] that is based on experimental data relating to the hydrologic role of autumn ploughing.

In future, as up until now, the greatest changes in the water balance are to be seen in the southeastern area of the Volga basin and in the Salsk steppe. Streamflow here can drop by 40 per cent, and soil moisture increase by six to eight per cent. This will greatly benefit farming.

The Don is expected to undergo more changes in water balance and streamflow than any of the other large rivers in the European part of the Soviet Union. This is not surprising since 70 per cent of the Don basin is cultivated, and 40 to 45 per cent of the area is ploughed in autumn. Lesser changes are expected in the Volga and Dnieper regions.

The Volga discharge will drop by 18 cubic kilometres a year as a result of an expansion of non-irrigated farming. When reservoir evaporation and water for public use and irrigation are added, the Volga flow will decrease by approximately 40 to 45 cubic kilometres compared with the normal flow before 1950. The level of the Caspian Sea will continue to drop. This deficiency will be partly made good by the diversion of water from the Vychegda and Pechora rivers to the Kama, a tributary of the Volga.

The flow of the Don river will decrease by about eight cubic kilometres and of the Dnieper river by five cubic kilometres. Agriculture will benefit from this. Soil moisture resources will increase in regions where farming needs them most.

Similar studies of river streamflow changes have been carried out abroad. An analysis of precipitation and the flow of the Saale river compared with crop yield fluctuations in its basin showed that climatic causes alone do not explain the flow changes observed

between 1885 and 1940, and that a growth in crop yields substantially influences streamflow. It is estimated that farming led to a 16 per cent drop in the annual flow of the Saale. As a result of more productive farming the flow of the Lippe river, a tributary of the Rhine, was 48 millimetres less (in terms of depth in relation to drainage area) in 1947-1948 than in 1919-1921; this was a 12 per cent drop.

Polish researchers have calculated that farming has reduced the flow of the Notec river by 38 per cent since 1883-1892. Scientists in other countries have made very few studies of water balance changes and streamflow reductions caused by farming, and it is therefore impossible as yet to make a well-substantiated forecast of the changes to be expected as farming grows more productive.

Our purpose in citing the above examples is to stress how important further study of this question is. The world's increased crop production on non-irrigated land by the year 2000 will, according to the estimates presented in the preceding chapter, be accompanied by a decrease of about 700 cubic kilometres in flood flow, and by a drop of 2,600 cubic kilometres if we count the water used in irrigation farming. This will be more than 10 per cent of the volume of stable river flow, which we estimate at between 23,000 and 24,000 cubic kilometres by the year 2000.

Drainage of swampland will also change the local water balances. Although the drainage factor has not yet been studied in depth we can make an approximate assessment of its impact.

The Soviet Union, Poland and other countries have big swamp reclamation programmes. All of the world's marshland suitable for cultivation will probably have been reclaimed by the beginning of the next century. However, drainage will not, evidently, affect the

water balance or the state of the water resources to any appreciable degree.

What does change substantially when swamps are drained is the nature of evaporation. Evaporation from undrained swamps and swampy land is almost entirely waste. But a considerable part of the water used by reclaimed marshland that has been turned into cultivated meadows and ploughland is transpiration. This indirectly adds to the water resources. Water that once evaporated from swamps with no benefit to man is drawn into the economy as part of the hydrologic cycle and contributes to greater crop production.

MAN STORES GROUNDWATER

Man has been storing groundwater on a small scale for a long time. It is the practice in the Kara Kum, a desert in Central Asia which is unusually poor in water. Here surface runoff from rain or snow accumulates for a brief time almost every year in the lower sections of *takyrs*, as areas covered with a clayey drift are called. Under natural conditions almost all of this water quickly evaporates, but the local inhabitants, to whom every drop of water, particularly fresh water, is precious, dig pits in the lower sections of takyrs. The runoff collects in the pits and then seeps down to form a layer of groundwater, usually on top of the saline groundwater that is widespread in the Kara Kum. Since its density is less than that of saline water, the fresh water floats on top of the latter. Wells are dug to bring up the fresh water, but they have to be used with great care not to drain the saline water below the fresh water.

An improved method of storing and using groundwater developed by V. N. Kunin is now widely used.[6,53] In some cases small catchment basins are covered with asphalt to reduce losses.

Groundwater storage is practised on a fairly wide scale in Eastern Siberia and the Soviet Far Eastern regions.

A little under 300 groundwater reservoirs were in use in the United States in 1958, chiefly in the Western states. They are to be found in Asia, Turkey, the Federal Republic of Germany and elsewhere.[54]

The semi-regulated storage and exploitation of groundwater will be expanded, of course, and new methods developed. Ways will be found of pumping water into rock formations to create large underground reservoirs both for water supply and for increasing the groundwater component of streamflow.

There are several advantages to large-scale underground water storage. First of all, it provides water of a higher quality for supply systems. Although we assume that sewage will not be dumped into waterways in future, pollution of surface water can hardly be eliminated altogether. There is no completely satisfactory way as yet of cleansing storm water and snowmelt runoff from municipal territory and preventing it from reaching streams and lakes. With the increased use of weed and pest killers it will be difficult to prevent chemicals from getting into surface water.

As groundwater flows through a porous medium to the site of intake it undergoes a measure of self-cleansing. This is one of the advantages of using groundwater in public water supply systems. But groundwater storage cannot cover future water requirements. If it is over-exploited there will be less groundwater to feed streams and a less stable river flow.

It is very difficult to control the entire streamflow by means of surface reservoirs and soil improvement measures. Yet in future all river water will have to be regulated to ensure a dependable flow not only from season to season but also, where possible, from

year to year. Groundwater reservoirs lend themselves to such regulation. Groundwater can be stored in seasons or years when water is plentiful and used in low-water periods. Because groundwater moves so slowly it is easy to regulate. Since underground reservoirs require no surface area they do not affect land use. Another advantage is that water in underground reservoirs is free from evaporation, through which ordinary reservoirs lose a substantial share of their available capacity.

It is hard to make a fully substantiated estimate of how much groundwater will have to be stored in future. In the closing decades of our century an annual average of 5,000 cubic kilometres of surface flood water may have to be channeled into underground reservoirs.

TRANSPORTATION OF WATER

The geographic distribution of the earth's water resources is extremely uneven. Some regions do not have enough while others have too much. Shortage and surplus are relative to demand, of course. There are regions generously endowed with water, but the cities, industries and farming have grown to such an extent that the resources fall short of the requirements.

Therefore, besides managing the hydrologic cycle, changing the structure of the water balance, and regulating streamflow, man must distribute water resources more evenly. He can do this, in part, by planning the siting of communities and industries. However, planners often concentrate on such factors as raw materials, manpower, electricity and transport facilities, an dfail to take due account of the water factor, regarding water as an inexhaustible gift of nature.

On the other hand, populations and industries cannot always be sited in places having a good water

supply. Mining, for example, often has to be developed in areas with a water shortage. The Karaganda coalfields in Siberia are a case in point. A canal about 500 kilometres long has been built to divert water from the Irtysh river to the coalfields and a number of industrial plants. On the way to Karaganda the canal provides the Ekibastuz coal mines, the Bazshakul copper mines and other industrial sites with water. This is a costly project because pumping stations with a total capacity of 340,000 kilowatts had to be built to lift the water a total of 475 metres.

Water has to be transported over long distances to arid regions where warmth-loving crops, primarily cotton, are grown. Construction of a 1,000-kilometre canal in the Soviet Central Asian republic of Turkmenia, running through the vast Kara Kum desert from the Amu Darya river to the Caspian Sea through Murgab, Tejen and Ashkhabad, is now nearing completion. Other major Soviet irrigation canals include the Great Ferghana Canal in Central Asia and many in Transcaucasia and along the lower reaches of the Dnieper.

As for shipping canals, there are the Volga-Don, Volga-Baltic and White Sea-Baltic canals in the Soviet Union and a large number in Western Europe, Southeast Asia and North America. Shipping canals are usually designed to maintain definite navigation depths and to feed locks, but not to move water. Some, though, like the Volga-Moskva Canal, combine navigation with the delivery of water.

Water is moved long distances in California to supply cities, industries and farming. Large pipelines have been built in Bulgaria to carry water to the Dobrudja farming area. In the northern part of the Soviet republic of Kazakhstan there are thousands of kilometres of centralized pipeline systems that supply hundreds of state farms.

Future projects will deliver water over still greater distances. There is a plan in the Soviet Union to move approximately 30 cubic kilometres annually from the northern Pechora and Vychegda rivers to the Kama river to supplement the water deficit expected in the Volga in future and to maintain the level of the Caspian Sea. The latter purpose cannot, of course, justify the use of a large volume of pure water in such a thickly-populated industrial area as the European part of the Soviet Union; it would be too high a price to pay for maintaining the Caspian Sea level. As more water is consumed in the basins of the Volga, Ural, Kura and other rivers of the Caspian basin, the level of the Caspian Sea will drop, and this will have to be recognized. The same is true of the Sea of Aral. Even after water is diverted from the basin of the Ob river in Siberia to the basins of the Syr Darya and Amu Darya rivers in Central Asia—and we are certain the time will come when this scheme will not seem so fantastic—Ob water will be used for more important purposes (public water supply, irrigation and industry) than to maintain the level of the Aral and Caspian seas.

However, these large bodies of water cannot be ignored. They are important waterways and must be preserved. But to preserve them in their original form would mean consuming a large amount of precious fresh water that is needed for more important purposes. The problem of the Caspian and Aral seas can be solved by reducing their level and area to a point at which the water lost in evaporation does not exceed the inflow of river water.

As time goes on, the Soviet Union's southern districts will need more and more water from northern rivers. Moving water from the Pechora and Vychegda rivers into the Kama will be only the first of similar

projects. It is possible that water will have to be diverted from the lower reaches of the Ob to Central Asia and also across the Ural Mountains to the European part of the Soviet Union.

There are plans to deliver water from Alaska to the drought-afflicted western areas of the United States. Experts are studying the technical and economic possibilities of towing icebergs that have broken off from glaciers in southern Alaska and Greenland down to the coast of North America to supply droughty areas. In time special docks may be built at ports in California for icebergs towed down from the North.

In the more distant future it will probably be feasible and expedient to build nuclear plants to melt northern glaciers and pipe the water to where it is needed.

In Africa, it will evidently soon be possible to move water from the Niger and Congo rivers to the Sahara.

The piping of municipal sewage to irrigate farm fields will be widely practised.

It is hard to envisage all the ways in which water will be moved from one place to another, but it is certain that this will be done on a large scale. Besides canals, large-diameter pipelines will no doubt be widely used.

Water will become an item of foreign trade; countries with insufficient supplies will import it from water-rich countries. Since natural resources are widely exchanged in foreign trade it is only logical that this should apply to water as well. The problem has arisen only in a few cases so far, but in future foreign trade in water will undoubtedly be a regular practice.

To recapitulate, man's dependence on the distribution of water resources is relative. By moving water he can free himself from this dependence. It is common for water to be sent through canals and pipelines. The scale on which water is moved will grow immea-

surably in future. Canals and water pipelines will hold an important place in hydroeconomic projects.

WATER RESOURCES AND MOISTENING RHYTHMS

When we speak about changing the water balance and the regimen of rivers we proceed from the more or less short-term, recurring fluctuations typical of climatic and hydrological phenomena; several droughty, low-moisture years are succeeded by years with an abundance of water and moisture. This pattern contributes to the natural regulation of the groundwater component of the water balance and also to the regulation of streamflow by the use of reservoirs. The aim of long-term management is to accumulate water in the good years for use in the poor years. And the more often droughty periods are succeeded by periods of abundance the easier it is to regulate streamflow.

As the science of geography has discovered, there also exist *rhythms of moistening*, with cycles lasting from 1,800 to 2,000 years. They have been studied in depth by Shnitnikov, a Soviet geographer who has traced them from the 12th century B.C. to our day.[55] He investigated a wide range of factors: fluctuations of lake levels, the position of lake and river terraces, the variability of sea and ocean transgressions and regressions, fluctuations in mountain glaciation, the distribution of forests (their location in past periods is determined by analyses of flower pollen in the depths of peat bogs), archaeological finds, etc.

A comparative analysis of all these phenomena enabled Shnitnikov to establish that in the current cycle, which started about 500 years ago, the continents had a high level of moisture until the late 18th and early 19th centuries, and have been experiencing a drop in the moisture level ever since.

The world's climate was warmer and drier at the

beginning of the present millenium than it is today. Mountain glaciers throughout the world had retreated and the amount of ice in the northern seas had diminished. This was what enabled the Vikings to sail the North Atlantic and discover Iceland, Greenland and then the east coast of North America. Rivers were shallow, as evidenced by the low level of the Caspian and Aral seas.

That is how Shnitnikov describes the present cycle. He cites numerous facts to show that a drop in the general moistening level of the continents is now taking place. His analysis of the patterns of rhythmic moisture fluctuations enables him to forecast the trend in water resources until the end of the present century and into the 21st century. He expects an impoverishment of the water balance of the continents in favour of the water balance of the seas. Therefore, we should expect a reduction in streamflow and a worsening of the water balance of lakes.[56,57]

A slow, systematic decrease in the amount of water in rivers and the amount of groundwater is taking place in the current phase of the modern cycle. This is a negative phenomenon, of course. The decrease in the amount of water will hardly be appreciable within the next few decades, but it certainly should be taken into account in planning water use and conservation. Hence, changes in the water balance and water regimen should be planned with something in reserve to compensate for a water shortage associated with moistening fluctuations. It is necessary to carry out further research into the fluctuation cycles and evolve methods of predicting the scale of the expected decrease in resources.

TOMORROW'S WATER BALANCE

The sweeping improvements that man could make in the water balance in the next few decades are summed up in Table 26. Here are the main points:

TABLE 26

LONG-RANGE FORECAST OF WATER BALANCE CHANGES

Items	Water Balance,* cu km		Changes
	present	future	
Precipitation	110,300	110,300	Conversion of 700 cu km of flood runoff into soil moisture on ploughland; increase of transpiration from forests and evaporation from reservoirs by 600 cu km
Total river runoff	38,800**	37,500**	
Stable runoff including:	14,000	22,500	Increase of stable runoff by 8,500 cubic kilometres through:
groundwater runoff into rivers and renewable ground-water stores	12,000	17,000	storage of 5,000 cubic kilometres of groundwater
lake- and reservoir-controlled runoff	2,000	5,500	regulation of 3,500 cubic kilometres of floodwater by reservoirs
Surface (flood) runoff	26,800	20,500	Use of 6,300 cubic kilometres of surface runoff, including 1,300 cubic kilometres retained as moisture in the soil and added to evapotranspiration, and 5,000 cubic kilometres stored as groundwater
Total moistening of territory	83,500	89,800	A growth of 6,300 cubic kilometres, consisting of 1,300 cubic kilometres of additional moistening of non-irrigated land and greater evaporation; the storing of 5,000 cubic kilometres of groundwater

CONTINUATION TABLE 26

Items	Water Balance,* cu km		Changes
	present	future	
Evapotranspiration	71,500	72,800	A growth of 1,300 cubic kilometres from higher crop yields and greater evaporation from reservoirs

* Round figures.
** This does not include the runoff of water (ice) from polar glaciers.

Reliable streamflow will increase from 14,000 cubic kilometres to between 22,000 and 23,000 cubic kilometres a year. This will be achieved mainly through regulating flood runoff by means of reservoirs, whose available capacity will grow by approximately 3,500 cubic kilometres, and through the storing of 5,000 cubic kilometres of groundwater. These changes will increase Grade I A water resources (see p. 101), which are the most available for use and therefore the most valuable.

We can assume that it will be possible to use between one-half and two-thirds of the groundwater stored by man. This is a high degree of efficiency.

Another major change in the water balance will be an increase of about 700 cubic kilometres in the soil moisture on non-irrigated land by reducing surface (flood) runoff correspondingly. There will be an increase of 250 to 300 cubic kilometres in evaporation from reservoirs and of 300 to 400 cubic kilometres in evapotranspiration from forests and meadows

made more productive by improvement measures. Soil moisture resources will increase by about 1,000 cubic kilometres. Besides, total moistening will increase by another 5,000 cubic kilometres through the storage of groundwater in man-made underground reservoirs.

A growth in soil moisture usually goes hand in hand with an increase in groundwater recharge. It is interesting to estimate how much groundwater recharge will grow with a rise of 1,000 cubic kilometres in soil moisture resources.

To do this we have to determine the coefficient of groundwater feeding of rivers (K_u). (See Chap. 3, pp. 75-76.) We get its average global value by dividing the groundwater flow into rivers (12,000 cubic kilometres) by the total moistening of territory (83,000 cubic kilometres) and obtain $K_u = 0.145$.

If groundwater recharge is greater than 12,000 cubic kilometres the coefficient K_u should be somewhat larger. If we assume that it increases to 0.2, the groundwater feeding of streams will grow by 200 cubic kilometres. In absolute terms this is a substantial quantity—twice as much as the amount irretrievably used in the public water supply for the more than 6,000 million inhabitants the world is expected to have by the year 2000. But this quantity amounts to only 1.7 per cent of the present groundwater flow into streams. For this reason we do not take the increase in groundwater recharge into account in our water balance changes forecast, considering that if it does come about it will go to compensate for the water that is inevitably lost when setting up underground reservoirs. This unaccounted-for gain in reliable streamflow resources will be a reserve in case we have overestimated the coefficient of stored groundwater.

The long-range changes in the Soviet Union's water balance in Table 27 are wholly feasible.

TABLE 27

FORECAST OF CHANGES IN THE SOVIET UNION'S WATER BALANCE (CU KM)

Items	Water balance	
	present	future
Precipitation	10,960	10,960
Total river runoff	4,350	4,200
Stable river runoff	1,400*	2.400*
including:		
groundwater runoff and stored groundwater runoff regulated by lakes and reservoirs	1,020 380	1,200 1,200
Surface (flood) runoff	3,330	2,800
Total moistening of territory	7,630	8,160
Evapotranspiration	6,610	6,960

* Including the flow regulated by lakes and reservoirs.

The nature of the changes in the water resources of the Soviet Union is the same, as a whole, as in the rest of the world. Stable runoff will show a gain of about 1,000 cubic kilometres through the regulation of flood flow (820 cubic kilometres) and the storage of groundwater (180 cubic kilometres). As a result, surface (flood) runoff will be reduced. Surface runoff will drop by another 200 cubic kilometres as more water goes on transpiration with the increased productivity of arable land and forests. For this same reason, and also because of groundwater storage, total moistening of territory will grow by 530 cubic kilometres. This, of course, is a very rough estimate but it indicates a trend and seems fully feasible.

Changes on such a scale may be necessary by the beginning of the next century.

The changes which we have predicted in Tables 26 and 27 are envisaged as taking place within the next few decades, up to about the year 2000. There will undoubtedly be further changes in water resources in the more remote future. The world's entire streamflow, not counting the flow from polar glaciers and part of the highest floodflow over and above the available storage of reservoirs, that is, excluding approximately 4,000 to 5,000 cubic kilometres, can in principle be regulated by reservoirs and by storing groundwater. Stable runoff, including stored groundwater, will then amount to about 30,000 cubic kilometres, that is, twice as much as it is today. But in the remote future it will evidently also be possible to plan weather control and additional precipitation in areas requiring more moistening. Artificial rain will then open up big prospects for regulating soil moisture resources. This will to a certain extent replace irrigation. It will probably be possible to solve another difficult problem, namely, that of reducing lake and reservoir evaporation and thereby increasing streamflow.

But these are changes about which we can only conjecture. It is impossible to make any sort of authentic estimate either of their scale or of when they will take place. Scientific and technological advances will undoubtedly lead to even more far-reaching changes in the water balance.

Finally, desalination of sea water and deep-lying saline groundwater is another reserve. Desalination cannot, of course, replace the vast natural reserves of fresh water, although some authors claim that it can. The idea is unrealistic because of the immense expenditure of energy that would be needed. The main

point, though, is that fresh water is an important component of man's environment. Conservation of the earth's ecosystems and their improvement in the interests of mankind require the conservation of fresh water, no matter whether it can be replaced from artificial reserves, the most promising of them being desalination.

Still and all, it will undoubtedly be useful to develop desalination processes, especially for areas where it is impossible to obtain fresh water by other means, such as transporting it from water-rich areas.

CHAPTER SIX

Will There Be Enough Water Tomorrow?

Everything said so far has prepared the reader for an answer to this vital question. We take an optimistic view, believing that if man uses the resources sensibly he will not be threatened by a water crisis.

A comparison of tomorrow's resources (Table 26) and consumption (Table 28) shows that man will have quite enough water to meet all his increased needs. Our estimates for the public water supply system are based on a doubled population and an eightfold growth in per capita consumption (up to 400 litres a day per person in future instead of the present 150 litres a day for the urban dweller and 50 litres for the rural inhabitant). We take gross industrial output to be 15 times greater than at present. Food needs are estimated for a doubled population according to a standard considered sufficient to fully satisfy human requirements. It should be remembered that today at least 40 per cent of the world population is undernourished, but it is believed that in future all people—and there will be twice the number there are today—will have as much food as they need.

Water intake to satisfy all of humanity's needs wil just about double, and irretrievable use will almos treble, including the amount to be transferred fron surface runoff to soil moisture to provide additiona water for arable land. Water requirements (irretrievable use) of all branches of the economy will amount to 6,200 cubic kilometres annually by the year 2000. Since stable streamflow will increase from the present 14,000 cubic kilometres to 22,500 cubic kilometres in future (Table 26), irretrievable use will amount to less than one-quarter of the available resources. However, our consumption estimates for some needs are evidently exaggerated; for example, that in the year 2000 irrigation farming will require an annual 3,800 cubic kilometres.

The existing resources are thus quite sufficient to meet all of mankind's needs for a long time to come; and all the more so if we take into account the water balance improvement potential.

This optimistic but fully realistic conclusion will hold true, however, only if the dumping of wastes into streams, lakes and reservoirs is stopped, for that, as we have seen, causes the greatest danger of exhaustion of water resources.

Our main conclusion also applies to a more remote future, when reliable streamflow plus stored groundwater will have been increased to about 30,000 cubic kilometres. This figure is wholly feasible in principle. We can estimate that the traditional resources, river water and groundwater, will be able to meet a demand 10 to 15 times greater than that expected by the year 2000. In other words, there will be water enough for a population much larger than the one the world will have at the end of the century.

This is a very rough estimate, of course, but it is hardly exaggerated since it is based on further pro-

gress in using and improving water resources—and there is no limit to improvement. More efficient ways and means of exploiting water resources, managing the hydrologic cycle and transferring some industries to dry production methods will undoubtedly be found. The improved water balance will then provide for a still larger world population.

Could every possibility of maintaining sufficient supply be exhausted and further population growth and economic development be limited by a lack of water? No, we do not think so. Further progress in methods of using and improving water resources should be regarded as an important reserve which might exclude the need to search for other sources of supply. If man fully exhausts the traditional water resources he will have other sources to turn to, sources that will not have to be tapped on a large scale within the next few decades. They include desalination of sea water and briny groundwater, and utilization of water from polar glaciers.

At present, desalination is too costly to be practised on a big scale. There are now about 100 desalination plants in the world, with an aggregate annual capacity of between 80,000,000 and 100,000,000 cubic metres of fresh water. This is less than one twenty-thousandth of today's requirements. Desalination is at present justified, as we have said, only where other sources of water are lacking or when the delivery of water is more expensive than desalting.

As the process is perfected and the demand for water increases, desalination will be used more widely, but it is not expected to be a large-scale source of additional water within the next few decades.

Another consideration is perhaps even more important. There will be quite enough water for all purposes in the coming decades without large-scale desalting

TABLE 28

WATER USE TODAY AND TOMORROW (IN CUBIC KILOMETRES)

Types of use	Today				Tomorrow			
	intake	irretrievable use	discharge of sewage	polluted water	intake	irretrievable use	discharge of sewage	polluted water
Water supply (all types)*	600	130	470	5,580	1,500	1,050**	0	0
Irrigation	2,800	2,100	700***	0	3,950	4,000****	400***	0
Non-irrigated farming*****	500 / 0	500 / 0	0	0	1,200 / 700	1,200 / 700	0	0
Hydropower and navigation	160	160	0	0	500	500	0	0
Fish-breeding and angling	65	15	50	0	175	85	90	0
Total	3,625	2,405	1,220	5,580	6,825	6,335	490	0

* Second forecast variant.
** Not counting 450 cubic kilometres of sewage used in irrigation.
*** Water returned after irrigation.
**** Including 450 cubic kilometres of sewage used in irrigation.
***** The numerator is the additional streamflow used in non-irrigated farming compared with past flow; the denominator is the same in comparison with present flow.

if the dumping of wastes into rivers is stopped and if the other steps discussed in the previous chapters are taken. It will obviously be inexpedient to divert an immense amount of energy in order to desalinate the vast quantities of water required to replace river water and groundwater. It will be enough to maintain desalination plants in the desert, where there is no other way of obtaining fresh water.

But if we expect to be unable to use streamflow resources because they are contaminated, and if we have to replace a greater part of this water with desalinated water, we can look forward to the gloomy prospect of living on the banks of polluted rivers.

Desalination is a good thing, but the idea of practising it on an extensive scale has a negative aspect in that it is often identified with the neglect of traditional water resources. It is a good method of obtaining fresh water locally when other resources are not available, but it is certainly not to be used to replace river water and groundwater.

The removal of large quantities of water from the seas for desalination would create a new chord of the hydrologic cycle in which the waters of the land area would be increased at the expense of a slow decrease in the volume of the world ocean and a drop in its level. A drop in sea level would increase the land area in the coastal zone. But the level might not necessarily drop because the reduction in land water as a result of the current moistening cycle will be accompanied by an increase in the volume of the seas. The sea water intake for desalting and the increase in the volume of the seas might cancel each other out.

Another water source—one that is highly tempting to use and which would, in principle, regulate the ocean level—is the polar glaciers. Nuclear plants to

provide power for melting glaciers would also help to increase the flow of water into the world ocean and to compensate, if need be, for the water removed for desalination. Since the volume of the polar glaciers exceeds 20,000,000 cubic kilometres they could supply water for hundreds, if not thousands, of years.

But we should remember that it would take even more electricity to melt glaciers than it does to desalt sea water. More than 100,000 million kilowatt-hours of electricity would have to be used to melt one cubic kilometre of ice. Large amounts of electricity would be required to transport the water from the glacier to the place where it would be used. Since scientific and technological progress has essentially no limits, this problem can undoubtedly be solved in the distant future when new water resources will have to be found.

Let us stop at this point. The farther we try to see ahead into the future the more our suppositions resemble science fiction. We have nothing against science fiction, of course. For one thing, it often blazes a trail for science. And new trails will certainly have to be blazed if traditional water resources run out and desalination and the melting of polar glaciers have to come into their own.

We are convinced that no disastrous shortage will arise because there do exist the possibilities of adding new water resources to the traditional ones.

Mankind is not threatened by a water crisis. There is no need to be alarmed by the prospect of the blind alley which some futurologists claim the world will face when a rapidly growing population and expanding economy have to be supplied with water.

Our optimistic conclusion is based on a scientific analysis of present-day water use and conservation and the improvements that we can expect in future.

However, when we say that mankind is not threatened by a water crisis we do not want the reader to interpret this as meaning that the vitally important water problem can be neglected.

If today's imperfect water management practices persist, and if the principles of water use and conservation are not adapted to the conditions of the future, a water crisis is indeed inevitable, and it could come long before the time when world's population reaches 20,000 million, as some sociologists predict.

The figures in Table 19 show that if man continues his present water use and conservation policies, the danger of a water shortage, chiefly because of river pollution, is quite possible when the earth's population reaches 5,000 or 6,000 million, and there is a six- to ten-fold industrial growth, that is, possibly before we enter the 21st century. Even if man dumps only treated waste water into rivers (today probably more than half of it is untreated) he will eventually turn them into sewage mains.

And even if he obtains abundant water from other sources, such as desalination of sea water, the prospect of living beside dead rivers and lakes is a bleak one indeed. But this gloomy prospect, which might well become a reality if the present principles of water use and conservation remain in force, can be avoided by applying more advanced principles which are specifically designed to prevent a water crisis.

To recapitulate, the main principles which we feel should be followed in planning the use and conservation of water resources are:

1. If the water component of the environment is to be conserved and improved and the biosphere conserved and made more productive, the amount of streamflow that is used to cleanse sewage dumped into waterways must be included in the hydroeconomic

balance. This would be one of the most important preconditions for stopping the discharge of sewage into waterways.

2. Streams, lakes and reservoirs should not be used for the cleansing of sewage. No wastes, treated or otherwise, should be pumped into them. All industrial plants must be switched to closed-cycle water supply systems. Domestic sewage can for the most part be used in irrigation. What remains can be used, after treatment, to supply industrial plants that do not need first-grade water.

3. Economical use of water resources is important. The amount of water consumed by industry should be reduced. Wherever possible, industries should employ dry methods of production.

4. Water use and conservation should be effected through multipurpose projects.

5. Further improvement of the hydrologic cycle is in order. Streamflow should be controlled by reservoirs, soil moisture resources increased by regulating surface runoff, and groundwater should be stored. Desalination of sea water should be developed as the need arises. The possibilities of using polar glaciers as a source of water should be studied.

6. The siting of populations, farms and industrial plants in accordance with the distribution of water resources deserves special attention. It should be remembered, though, that in future more and more water will be transported over long distances.

It is extremely important that the water requirements of an area, large country or subcontinent tailored to the existing water resources, account being taken of the possibility for their extended reproduction.

7. More attention should be paid to the economic aspects of water use and conservation. A price should

be set on water. As a temporary measure, until the dumping of sewage is discontinued, a fee should be charged for dumping, according to the degree of pollution it causes.

8. Finally, the protection of water resources against contamination and depletion should become a matter of concern for the country as a whole and each citizen individually. People should be taught to love nature from an early age.

Many complex scientific, technological, financial and organizational problems are involved in this programme. The programme has to be introduced gradually, with the future constantly in mind.

At the present time, conservation is the culminating point of water use; it begins with the appearance of waste waters. Once the genie has been released from the bottle it is hard to get him back in again. Would it not be better to stop dumping sewage into waterways?

Water conservation should be part of water use; it should be a preventive measure.

The organization and technique of water use should be based on the principle of conservation.

People must cease to regard water as an inexhaustible gift of nature. Water is a raw material that must be treated with even greater care than other raw materials because there is no substitute for it.

The eternal renewal of the world's water resources in the great hydrologic cycle should assure mankind a permanent supply of water. Besides, as we have seen, the hydrologic cycle can be managed on a fairly large scale, and this will contribute even more to a permanent water supply.

Extended reproduction of resources is the general theoretical principle underlying all measures to intensify water use and conservation. The amount of

water on earth cannot be increased, but it is fully possible to increase the volume of water resources available for use and to improve the quality of the water. In fact, this is now being done on a fairly wide scale.

By extended reproduction of water resources we mean an increase in the amount of the most usable water (groundwater, reliable streamflow, etc.) by drawing on water that is almost inaccessible and thus less usable (surface runoff, floodwater and swamp water).

In practical terms, extended reproduction of water resources includes the following measures: regulation of streamflow by means of reservoirs and land and water improvement; reduction of evaporation from lakes and reservoirs and also from the soil in areas of insufficient and variable moistening; the diversion of water from over-supplied areas to areas where there is a shortage; economical use of water in water supply and irrigation systems; the raising of irrigation system efficiency; a ban on the discharge of wastes into streams, lakes and reservoirs; artificial recharge of groundwater. The aim of all the above and similar measures is to increase available water resources and improve the quality of the water.

This purposeful and interconnected complex, based on scientific foundations of planning and design, will undoubtedly help man to solve complex hydroeconomic problems and, as we have noted, take an optimistic view of the possibility of meeting his water needs both as regards quantity and quality.

The measures outlined in this book, above all a ban on the dumping of sewage into streams, lakes and reservoirs, would probably cost less to implement than it would cost to treat the sewage before dumping into these waters.

In conclusion, we should like to note that the method of long-range forecasting widely applied in this book is employed to create models of the use and conservation of natural resources, in this case, water resources. Our calculations have shown that a long-range water development plan cannot rest on quantitative indices alone. Substantial qualitative changes, that is, a change in the principles of water use and conservation, are also needed. We have shown that only this approach can avert a water crisis, which is inevitable if the present principles remain in force.

In conclusion it should be noted that this book is one of the works advocating the *constructive* trend in geography[58]. The latter consists in developing interconnected nature transformation problems so as to use natural (in this case, water) resources more effectively. One of the factors underlying this research are scientific long-range forecasts which, as we see from the aforesaid, aid in defining the most feasible and effective ways to solve the water problem in the interests of all people.

Bibliography

1. G. G. Landsberg, L. L. Fishman, and D. L. Fisher, *Future Resources of the United States*, Vols. 1 and 2.
2. M. I. Lvovich et al., *Fundamentals of a Method of Studying the Water Balance and Its Changes.* Institute of Geography, USSR Ac. Sci., Moscow, 1963 (in Russian).
3. A. P. Vinogradov, *The Chemical Evolution of the Earth.* USSR Ac. Sci. Press, Moscow, 1959 (in Russian).
4. F. A. Makarenko, "Underground Water". In: *The Hydrologic Cycle*, "Znanie", Moscow, 1966 (in Russian).
5. R. L. Nace, "Water of the World". In: *Natural History*, January 1964.
6. V. N. Kunin, *Local Waters of the Desert and Problems of Their Use.* USSR Ac. Sci. Press, Moscow, 1959 (in Russian).
7. M. I. Lvovich, *Elements of the Regimen of Rivers of the World.* Gidrometizdat, Moscow, 1945 (in Russian).
8. L. K. Davydov, *Streamflow of Rivers of the USSR. Fluctuations and Influence of Physico-Geographical Factors.* Leningrad, 1947 (in Russian).
9. M. I. Lvovich, *Man and Water.* Geografizdat, Moscow, 1963 (in Russian).
10. S. V. Bass, *Intrazonal Features of Spring Surface Runoff in the Forest Zone.* Moscow, 1963 (in Russian).
11. M. I. Lvovich, *Physico-Geographical Atlas of the World.* Moscow, 1964 (in Russian).
    (a) Types of Water Regimen of the Rivers of the Earth and of the Soviet Union. Sheets 58-59 and 221.

(b) Sheets 60-61.
(c) Sheets 227 and 228.
12. M. I. Lvovich, "Streamflow of the World". *Priroda*, No. 5, 1960 (in Russian).
13. M. I. Lvovich, *The Water Balance of the Continents of the World and the Method of Studying It.* USSR. Ac. Sci., Inst. of Geogr., Soviet Geophys. Committee., Int'l Ass. of Scientific Hydrology IGGV. Moscow, 1971.
14. M. I. Lvovich, "World Water Balance" (General Report). *Symposium on World Water Balance* (Reading, 1970). Publication No. 93 IASH, Vol. II.
15. V. M. Kotlyakov, The Snow Cover of Antarctica and Its Role in the Present Glaciation of the Continent. Results of studies under the programme of the International Geophysical Year. *Glaciology*, No. 7, 1964 (in Russian).
16. G. V. Lopatin, *Sediments of the Rivers of the USSR.* Geografgiz, 1952 (in Russian).
17. M. I. Lvovich, *Rivers of the USSR.* "Mysl", Moscow, 1971 (in Russian).
18. O. A. Alekin and L. V. Brazhnikova, *Discharge of Dissolved Substances from the Territory of the USSR.* Moscow, 1964 (in Russian).
19. A. B. Abakyan and S. P. Ovchinnikova, "Data on Reservoirs of the World". *Gidrotekhnicheskoe Stroitelstvo*, No. 8, 1971 (in Russian).
20. V. I. Vernadsky, *History of Minerals of the Earth's Crust. History of Natural Waters.* USSR Ac. Sci., Moscow, 1933-1936 (in Russian).
21. M. I. Lvovich, "Water Balance of the Land Area". Materials for the Third Congress of the Geographical Society of the USSR, Leningrad, 1959 (in Russian).
22. M. I. Lvovich and others, *The Water Balance of the USSR and Its Changes.* "Nauka", Moscow , 1969 (in Russian).
23. E. A. Brikner, "The Balance of the Earth's Water Cycle". *Pochvovedenie*, Vol. 7, No. 3, 1905 (in Russian).
24. R. Fritsche, "Niederschlag, Abfluss und Verdunstung auf den Landflächen der Erde". *Zeitschr. für Gewässerkunde*, Bd. 7, N. 6, 1906.
25. G. Wüst. "Verdunstung und Niederschlag auf der Erde". *Zeitschr. der Gesselsch. für Erdkunde*, Nr. 1-2, 1922.
26. M. I. Budyko, *Heat Balance of the Earth's Surface.* Leningrad, 1956 (in Russian).
27. L. I. Zubenok, "The Water Balance of the Continents and Oceans". *Doklady Ac. Sci. of the USSR*, Vol. 108, No. 5, 1956. Also: Revised Chart of the Water Balance of the

Continents. *Transactions of the Central Geophysical Observatory.* Issue 263. Heat Balance, 1970 (in Russian).
28. F. Albrecht, "Der jahrliche Gang der Komponenten des Wärme- und Wasserhaushaltes der Ozeane". *Berichte des Deutschen Wetterdinstes*, Nr. 79 (B. II), 1961.
29. R. Nace, *Geological Survey*, U.S. Department of the Interior, New release, July 1968.
30. M. I. Lvovich, The Water Balance of the Earth and Natural Zones of the Territory of the USSR. In: *Contemporary Problems of Geography.* "Nauka", Moscow, 1964 (in Russian).
31. G. M. Chernogaeva, N. N. Dreer, G. Ya. Karasik, V. M. Kotlyakov, K. S. Losev, I. A. Loseva, G. M. Nikolaeva, *The Main Water Balance Features of the Separate Continents.* USSR Ac. Sci. Inst. of Geogr. Soviet Geophys. Committee. Int'l Ass. of Scientif. Hydrology IGGU. Moscow, 1971.
32. G. Ya. Karasik. *Water Balance of Africa.* USSR Ac. Sci. Inst of Geogr.—Soviet Geophys. Committee. Moscow, 1971.
33. G. M. Chernogaeva. *Water Balance of Europe.* USSR Ac. Sci. Inst. of Geogr.—Soviet Geophys. Committee. Moscow, 1971.
34. E. E. Alexeevsky, "Carrying Out Lenin's Programme". *CMEA Bulletin on Water Economy*, 1970, No. 5 (in Russian).
35. M. I. Lvovich, "The World's Water Resources and Their Future". *Izvestia of the Academy of Sciences of the USSR*, Geographical Series, No. 6, 1967 (in Russian).
36. M. I. Lvovich, "The Outlook on the Use and Conservation of the World's Water Resources". *CMEA Water Economy Bulletin*, 1968-2(3).
37. M. I. Lvovich, "The World's Water Resources and Their Future". *Gidrotekhnika i Melioratsia*, No. 6, 1971 (in Russian).
38. M. I. Lvovich, and N. I. Koronkevich, "Preliminary Prognosis of the Use and Conservation of the Water Resources of the Soviet Union in the Year 2000". *Izvestia of the Academy of Sciences of the USSR*, Geographical Series, No. 2, 1971 (in Russian).
39. M. I. L'vovic, "Le bilan hydrique du globe terrestre". *Annales de geographie*, 1968.
40. M. I. Lvovich, "Scientific Principles of the Complex Utilization and Conservation of Water Resources". *Soviet Geography: Review and Translation.* March, 1969.

41. S. S. Ghinko, *Taming the Rivers.* Gidrometizdat, Moscow, 1965 (in Russian).
42. R. Keller, *Water and the Water Balance of the Land.* (An Introduction to Hydrogeography) (in Russian).
43. V. Pokshishevsky, "The Future Population of the World". *Novy Mir*, 1966, No. 1 (in Russian).
44. V. A. Kovda, *The Origin and Regimen of Saline Soils.* Vol. I, USSR Ac. Sci. Press, Moscow-Leningrad, 1946 (in Russian).
45. O. Ryulé, *Bread for Six Billion.* Moscow, 1965 (in Russian).
46. M. A. Fortunatov, "The Problem of Building Reservoirs and Preliminary Results of a Study of Reservoirs in Different Parts of the World". *Proceedings of the First Scientific and Technological Conference to Study the Kuibyshev Reservoir.* Part I. Kuibyshev, 1963 (in Russian).
47. A. T. Turchanovich, "Principles of an Economic Water Balance". In: *Management and Use of Surface Water and Groundwater Resources.* USSR Ac. Sci. Press, Moscow, 1961 (in Russian).
48. *Pravda*, No. 77, March 17, 1972.
49. F. Engels, *The Dialectics of Nature.*
50. P. M. Borisov, "The Problem of Radically Improving the Climate". *WHO Transactions*, Vol. 94, No. 4, 1962.
51. V. V. Dokuchaev, *Our Steppes, Past and Present*, 1894 (in Russian).
52. A. I. Voeikov, Man's Influence on Nature. In the journal *Zemledelie*, Vol. 1, Books 2 and 4, 1894 (in Russian).
53. V. I. Kunin and L. G. Leshchinsky, *Temporary Surface Flow and Artificial Development of Groundwater in the Desert.* USSR Ac. Sci. Press, Moscow, 1960 (in Russian)
54. N. N. Favorin, "Irrigation and the Artificial Recharge of Groundwater". In: *Management and Use of Surface and Subsurface Water Resources.* USSR Ac. Sci. Press, Moscow 1961 (in Russian).
55. A. V. Shnitnikov, "Fluctuations in the General Moistening of Continents of the Northern Hemisphere". *Transactions of the Geographical Society of the USSR.* Vol. 16, Moscow-Leningrad, 1957 (in Russian).
56. A. V. Shnitnikov, "Probable Trends in Water Fluctuation on the Territory of the USSR". *Voprosy geografii.* Issue 73, Moscow, 1968 (in Russian).
57. G. K. Tushinsky, *The Cosmos and Rhythms of Nature on Earth.* "Prosveshchenie", Moscow, 1966 (in Russian).
58. I. P. Gerasimov, Constructive Geography: Aims, Methods, Results. *Izvestiya vsesoyuznogo geograficheskogo obshchestva*, No. 5, 1966.

TO THE READER

Mir Publishers welcome your comments on the content, translation and design of this book. We would also be pleased to receive any proposals you care to make about our future publications.

Our address is: USSR, 129820, Moscow I-110, GSP, Pervy Rizhsky Pereulok, 2, Mir Publishers

Printed in the Union of Soviet Socialist Republics

OTHER BOOKS FOR YOUR LIBRARY:

THE QUEST OF THE QUANTUM

L. Ponomarev

A presentation of quantum theory for young people in which the expert may find unexpected facts. While telling the history of the atom with strict exposition of the facts, the main aim is to show the evolution of the ideas and notions of quantum mechanics and atomic physics and their development into a single, simple, harmonic system. Hence its division into Facts, Ideas, and Reflections. The author, L. I. Ponomarev, Cand. Sc., works in the laboratory of theoretical physics at the Joint Institute for Nuclear Research in Dubna. This is his first excursion into the difficult genre of popular science.

PHYSIOLOGY FOR EVERYONE

B. Sergeev, D. Sc.

A popularly written presentation of the facts and conundrums of physiology by Prof. B. Sergeev, D.Sc. (Biol.), a specialist in the evolution of functions and oceanologist. Intended for young readers and others interested in learning something about physiology without tears.